

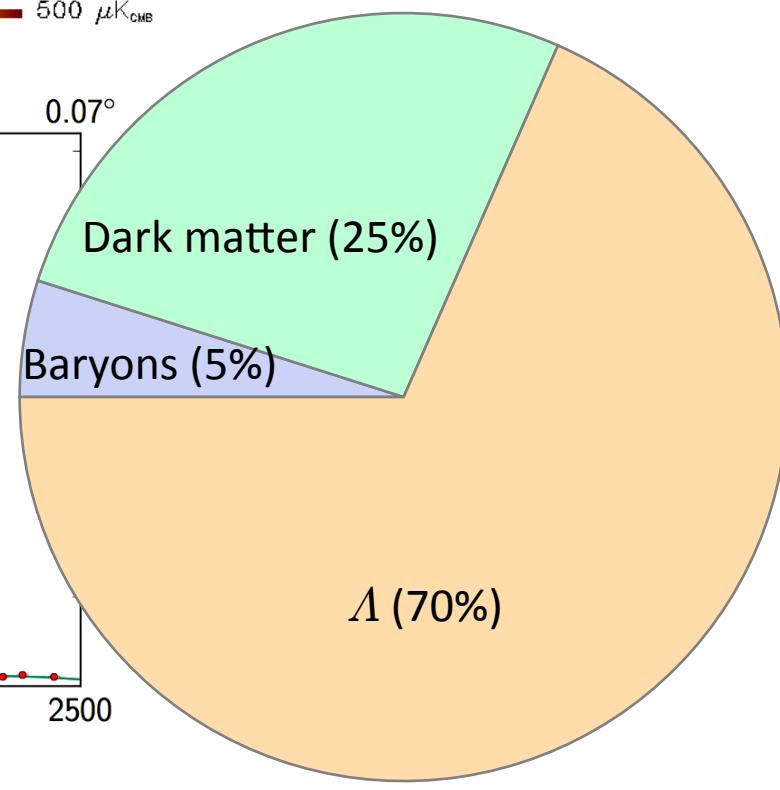
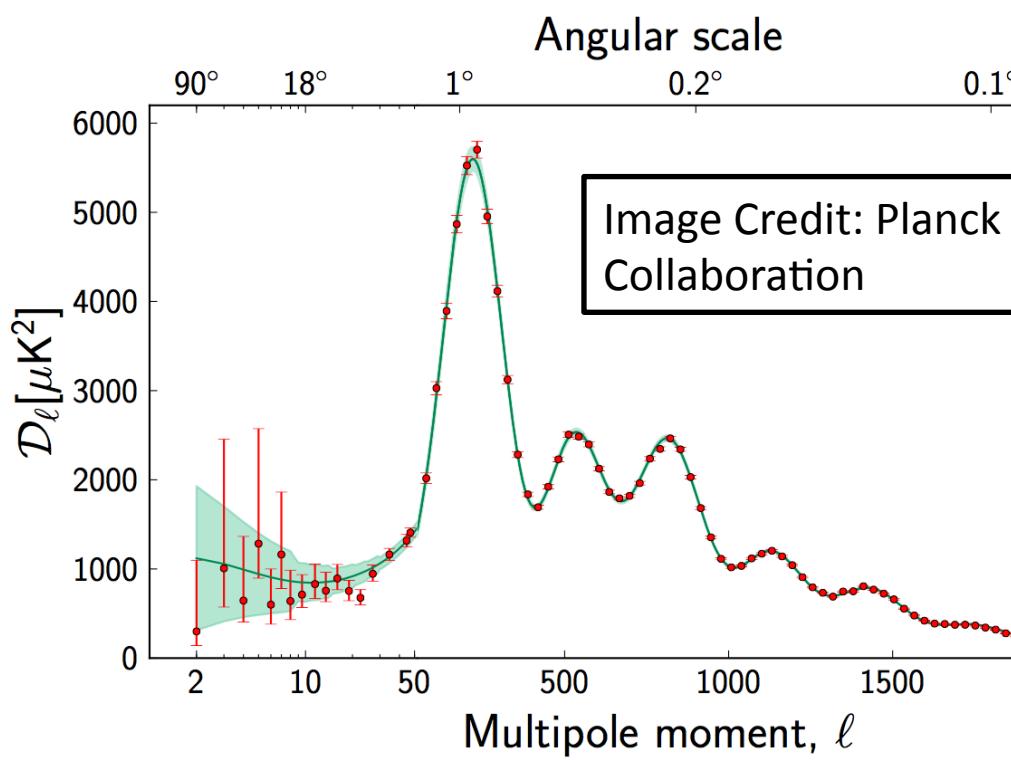
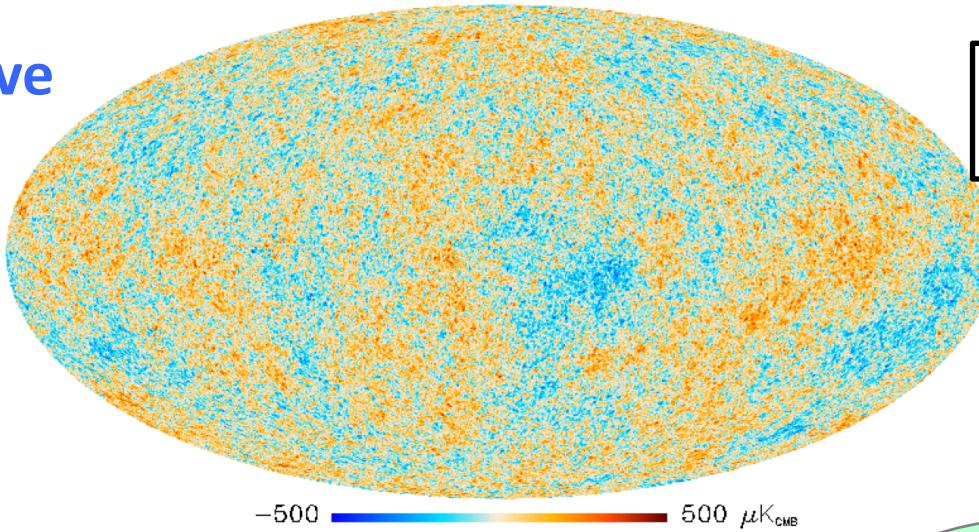
# Dark Matter and Pulsar Model Constraints from Galactic Center Fermi-LAT Gamma Ray Observations

Chris Gordon

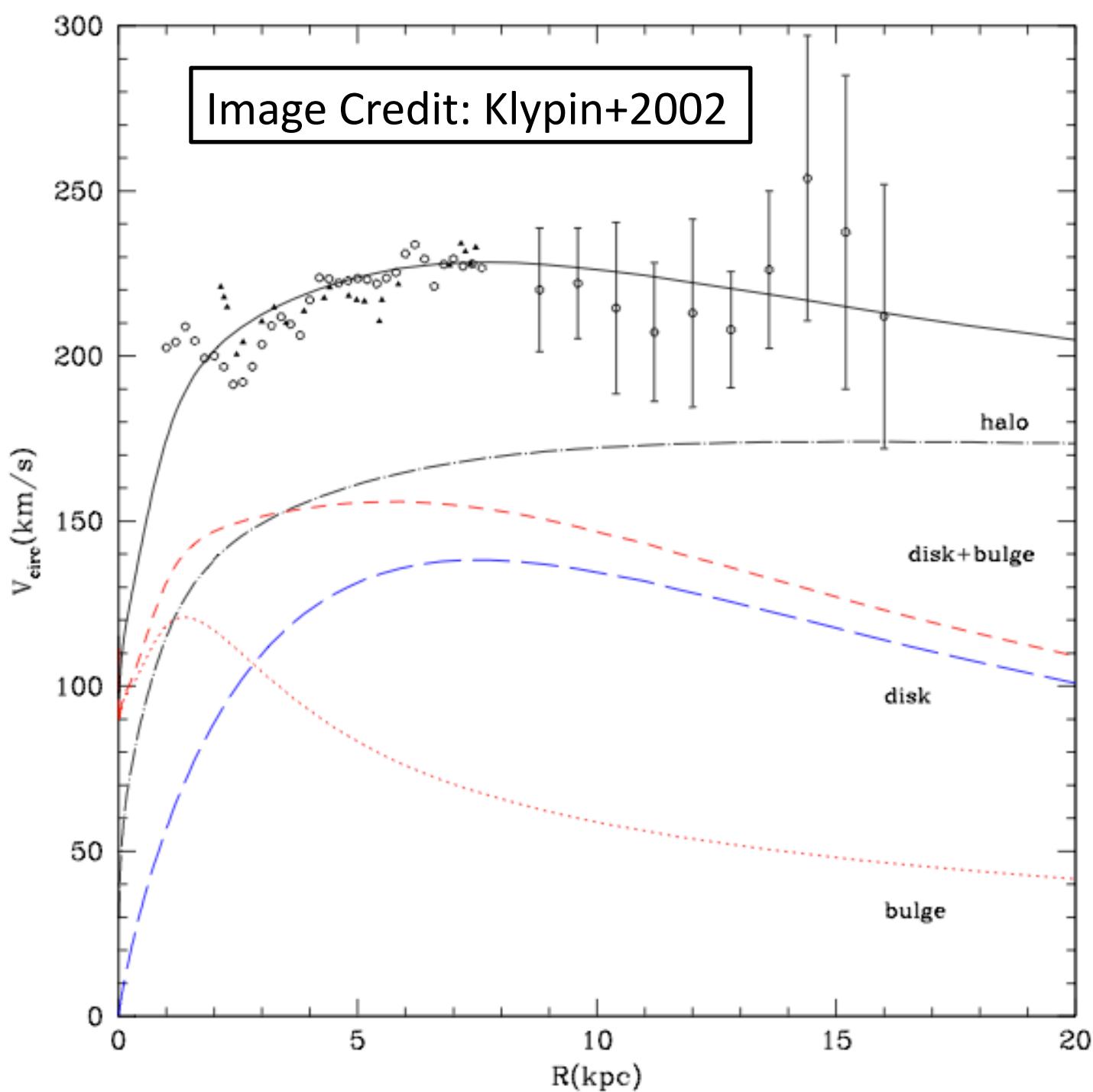
CG and Oscar Macias, arXiv:1306.5725, PRD in press.

# Evidence for Dark Matter

Cosmic Microwave  
Background



# Galactic Rotation Curves

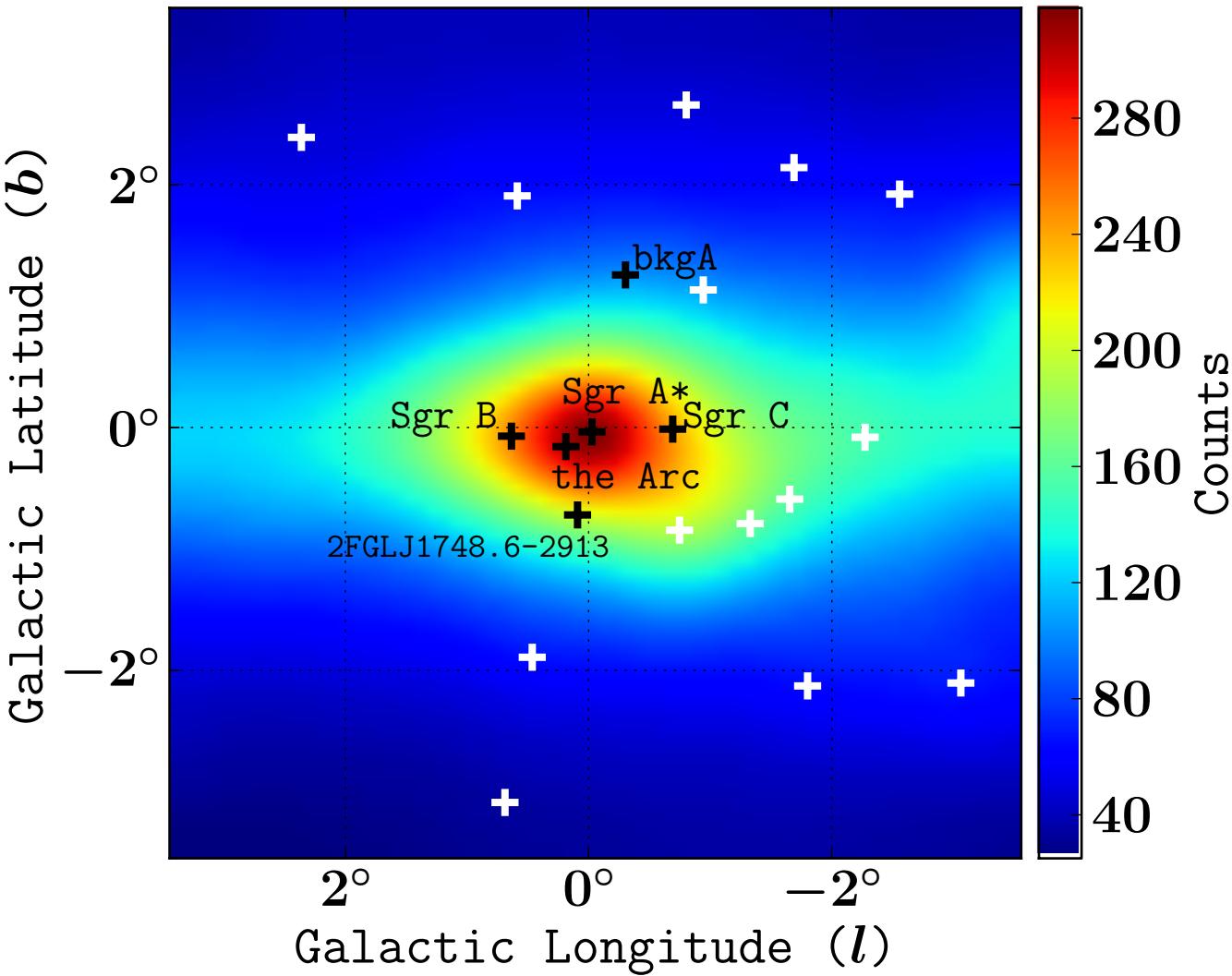


# What is the Dark Matter?

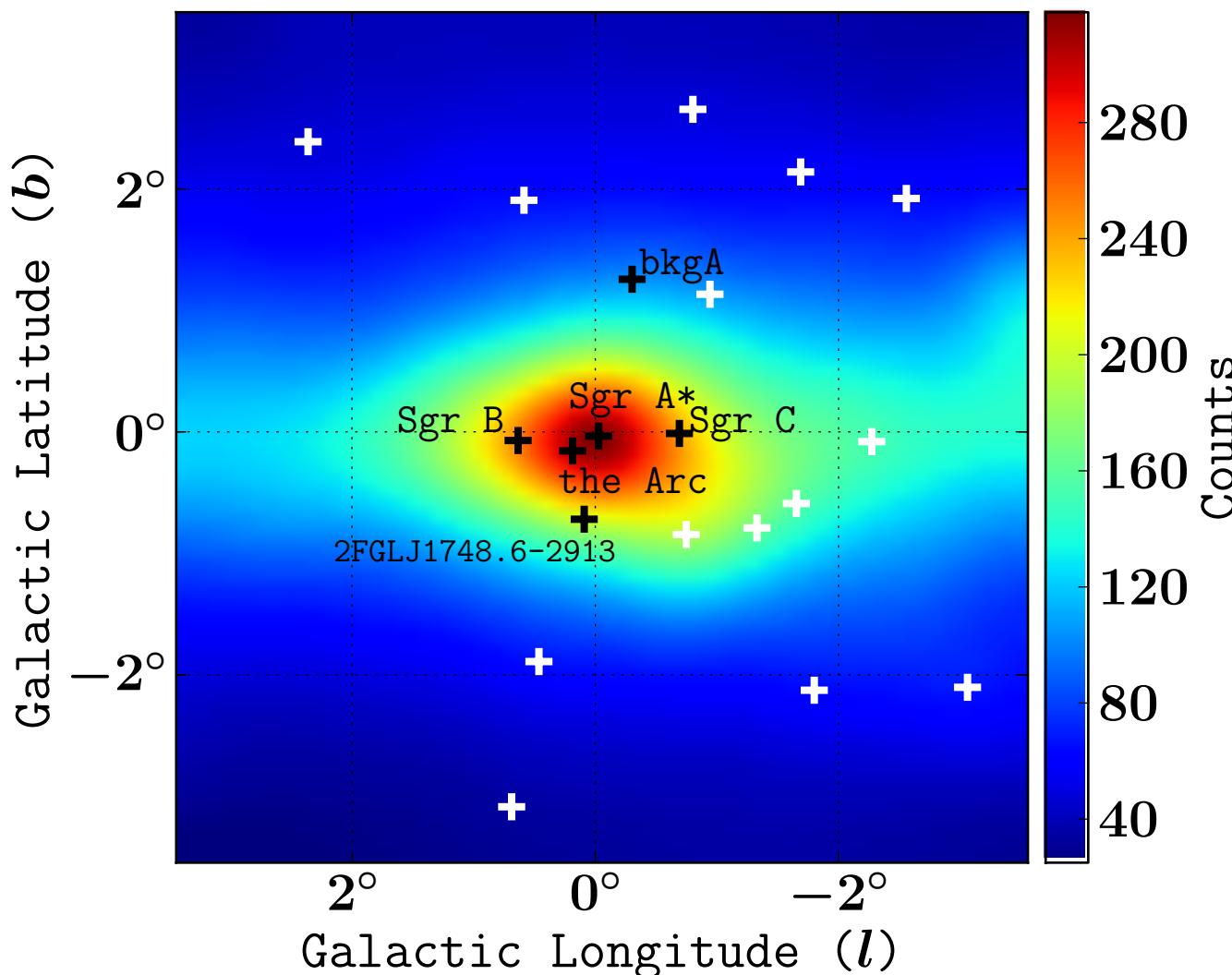
- Doesn't interact electromagnetically (dark).
- Doesn't interact via the strong force .
- Currently only its gravitational effects have been measured.
- Weak interactions possible. This would imply that pairs of dark matter particles can self-annihilate to ordinary matter.
- Modeling the evolution of the dark matter self-annihilation shows that a weak interaction cross-section for self-annihilation would naturally explain the dark matter abundance.
- Can't be the neutrino as dark mater needs to have its rest energy much greater than its kinetic energy.
- Generically known as a Weakly Interacting Massive Particle (WIMP).

# Excess Emission from Galactic Centre

- Vitale et al.  
(2009)
- Hooper and  
Goodenough  
(2011); Hooper  
and Linden  
(2011)
- Abazajian  
(2011)
- Abazajian and  
Kaplinghat  
(2012)
- Hooper, Kelso,  
Queiroz,  
Farinaldo (2013)

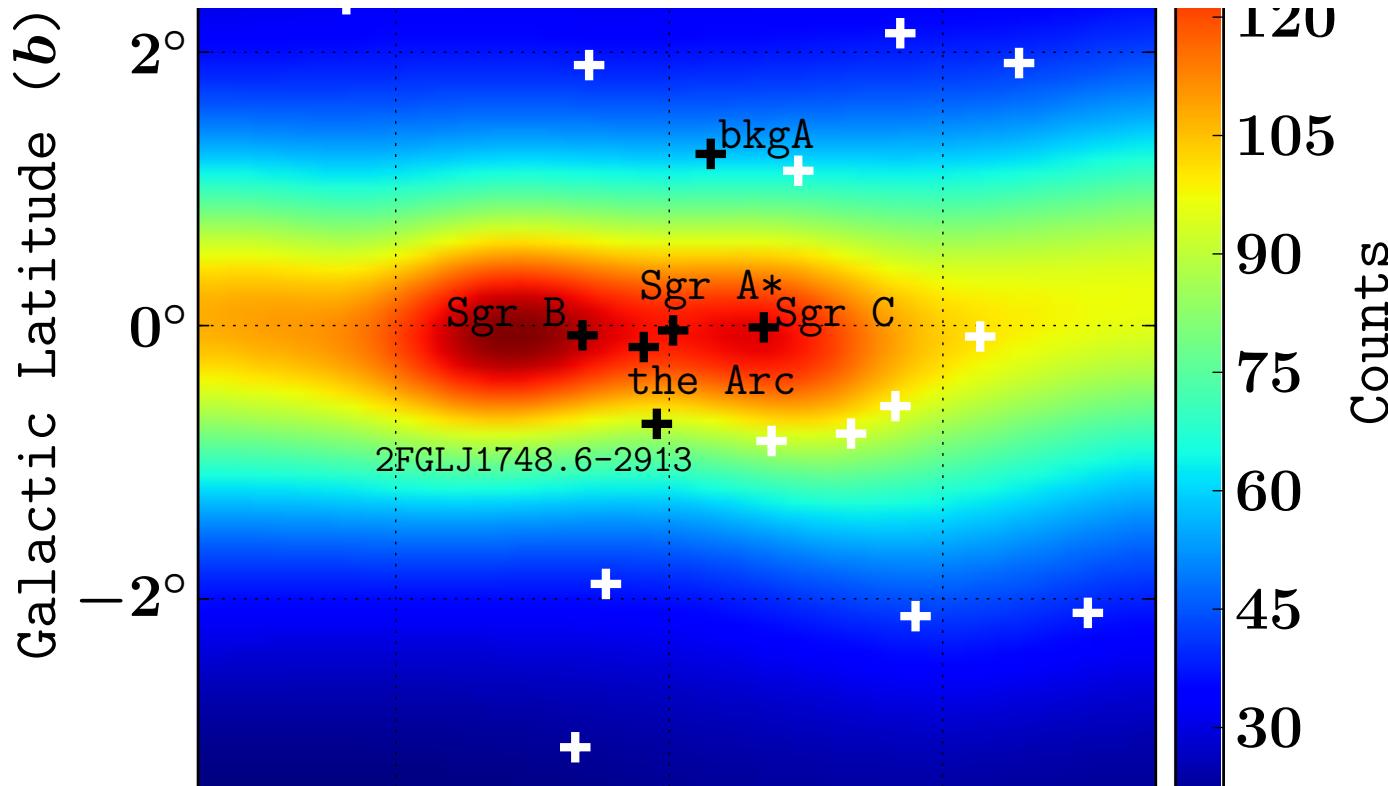


# Data



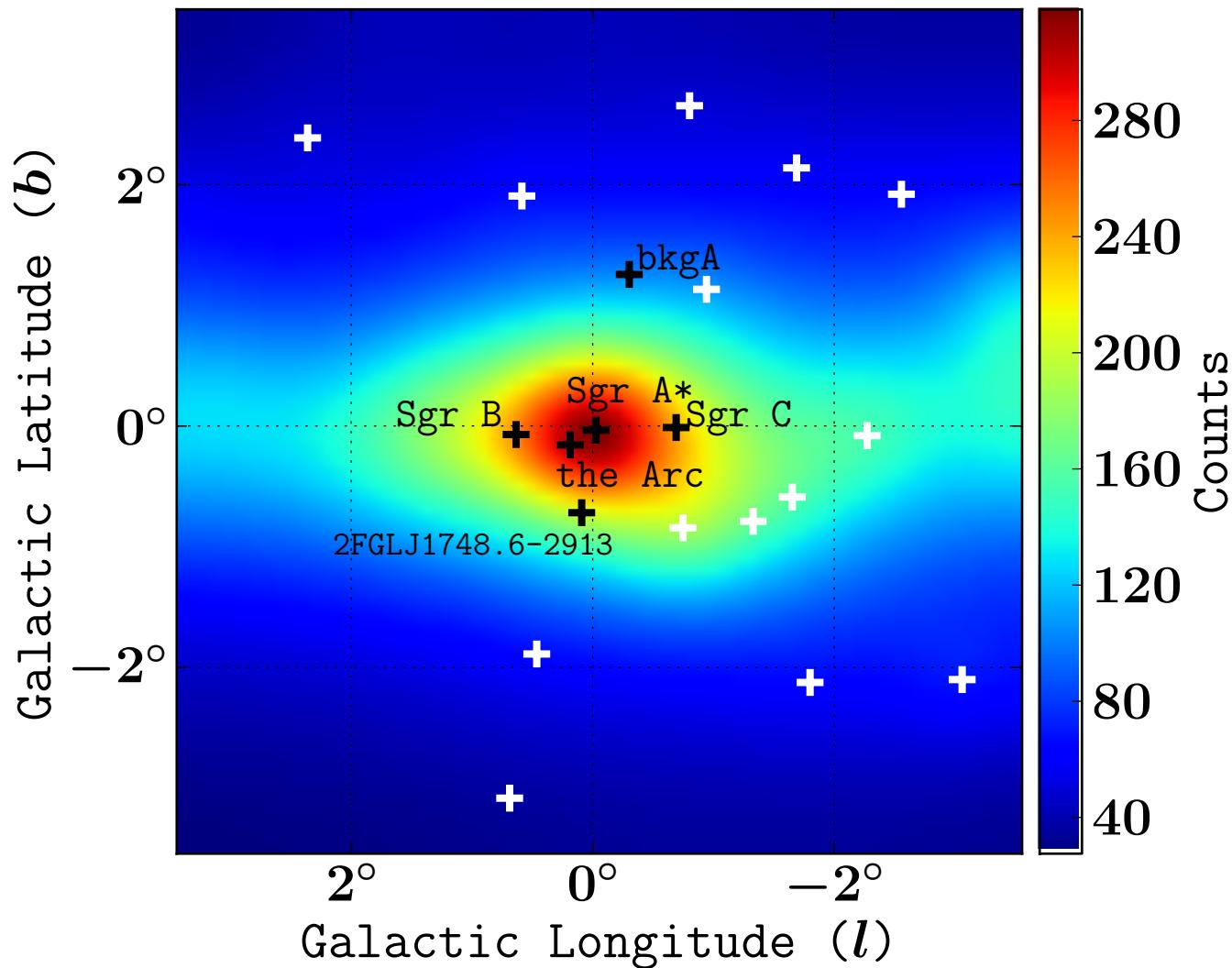
- Used Fermi-tools with 45 months of data (pass 7) and SOURCE event class, 300 MeV to 100 GeV. Usual zenith angle and space ship rocking angle restrictions applied.

# Diffuse Galactic Background



- Supplied with Fermi tools: Gamma-rays from the interaction of cosmic-ray electrons and protons with interstellar nucleons and photons .
- Generated from a linear combination of gas column densities, an Inverse Compton (IC) intensity map, and isotropic intensity to the Fermi LAT all sky data.

# Model



Model = DM (or MSP) + point sources + diffuse Galactic background+ extra-Galactic background

# Dark Matter Annihilation

Gamma ray Flux:

$$\Phi(E_\gamma, b, l) = \Phi^{PP}(E_\gamma) \times J(b, l),$$

$$\Phi^{PP}(E_\gamma) = \frac{1}{2} \frac{\langle \sigma v \rangle}{4\pi M_{DM}^2} \sum_f \frac{dN_f}{dE_\gamma} B_f,$$

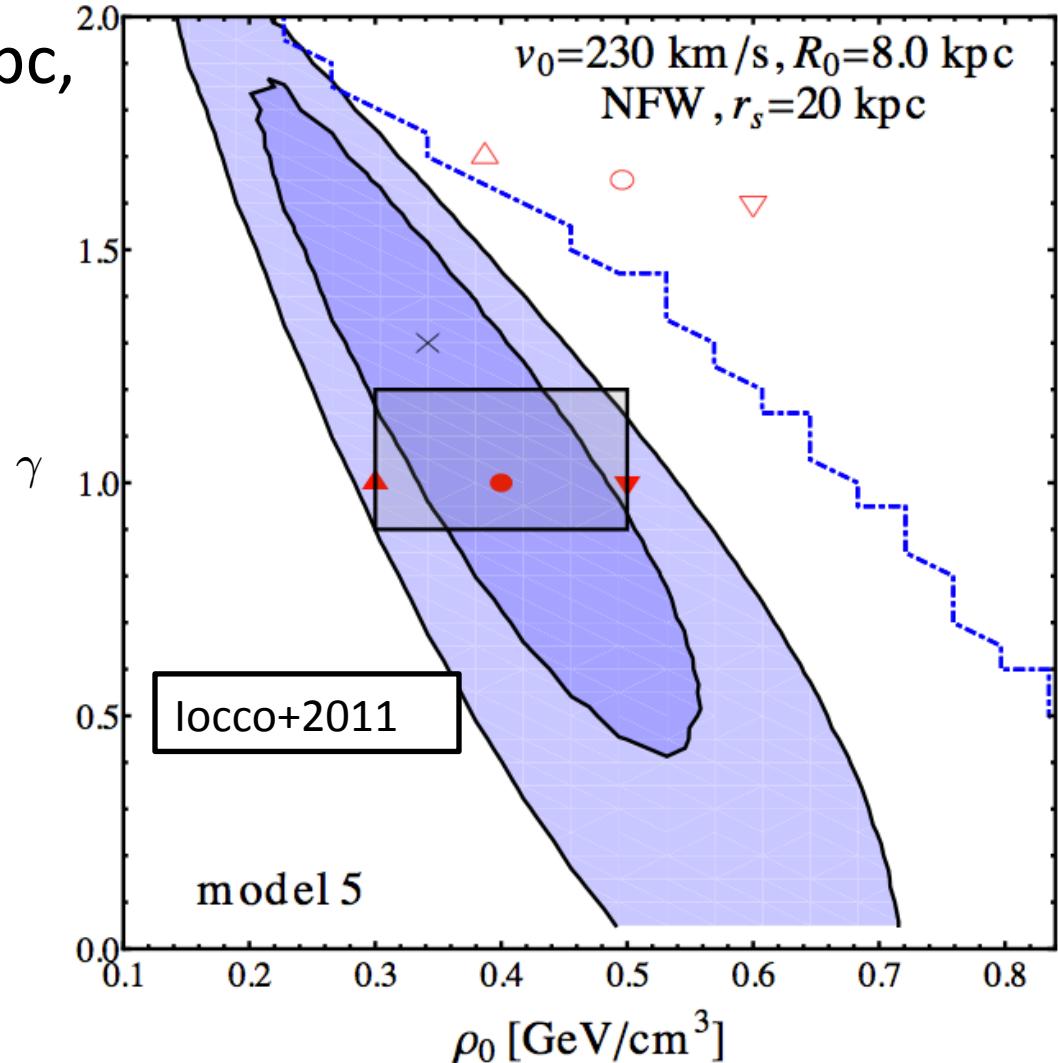
$$J(b, l) = \int_0^\infty ds \left. \rho(r)^2 \right|_{r=\sqrt{R_\odot^2 - 2sR_\odot \cos(b)\cos(l) + s^2}},$$

Distance of solar system to Galactic center:  $R_\odot = 8.25$  kpc.

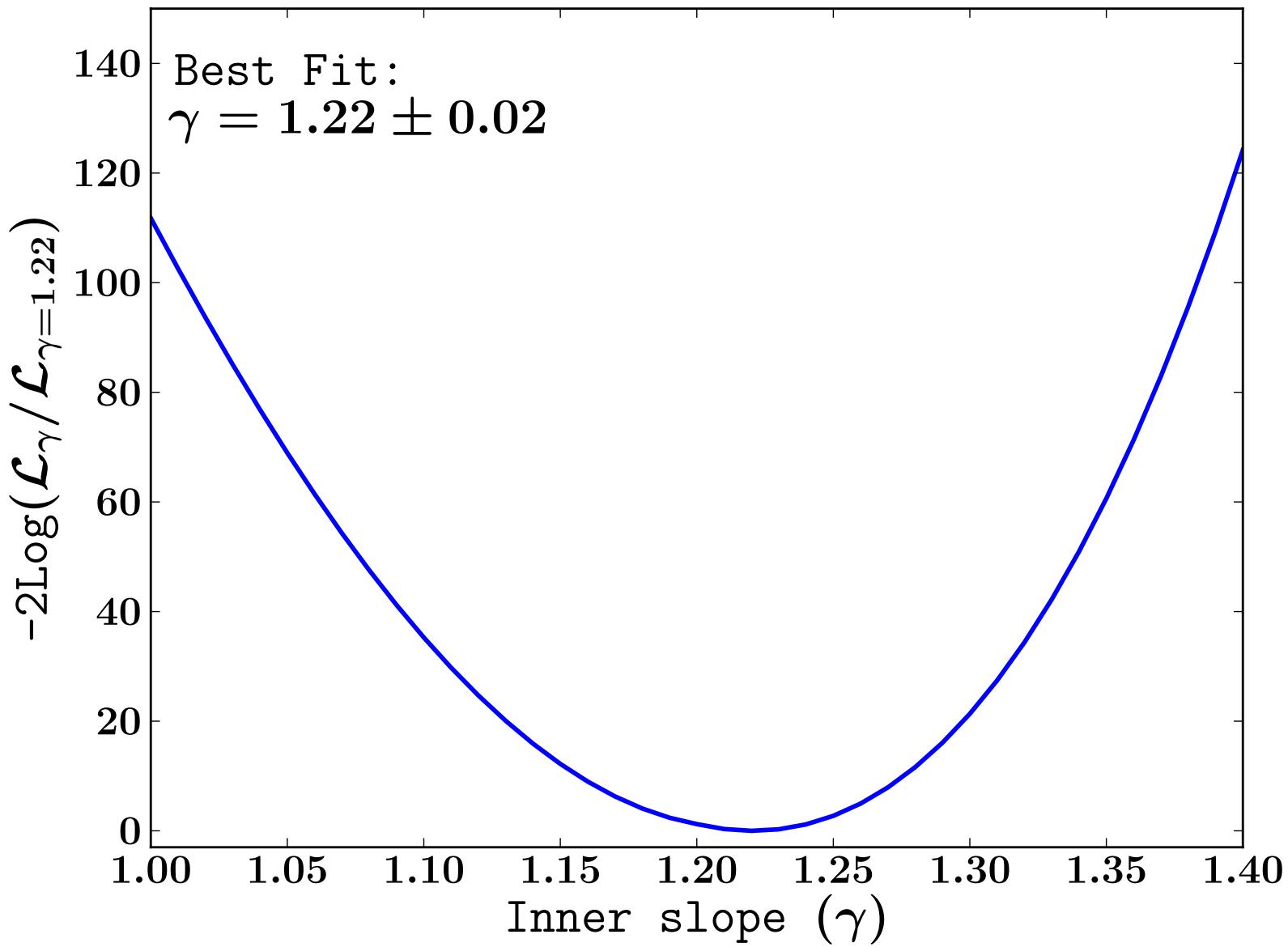
Gen. NFW:

$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^\gamma \left[1 + \left(\frac{r}{r_s}\right)^\alpha\right]^{(\beta-\gamma)/\alpha}}$$

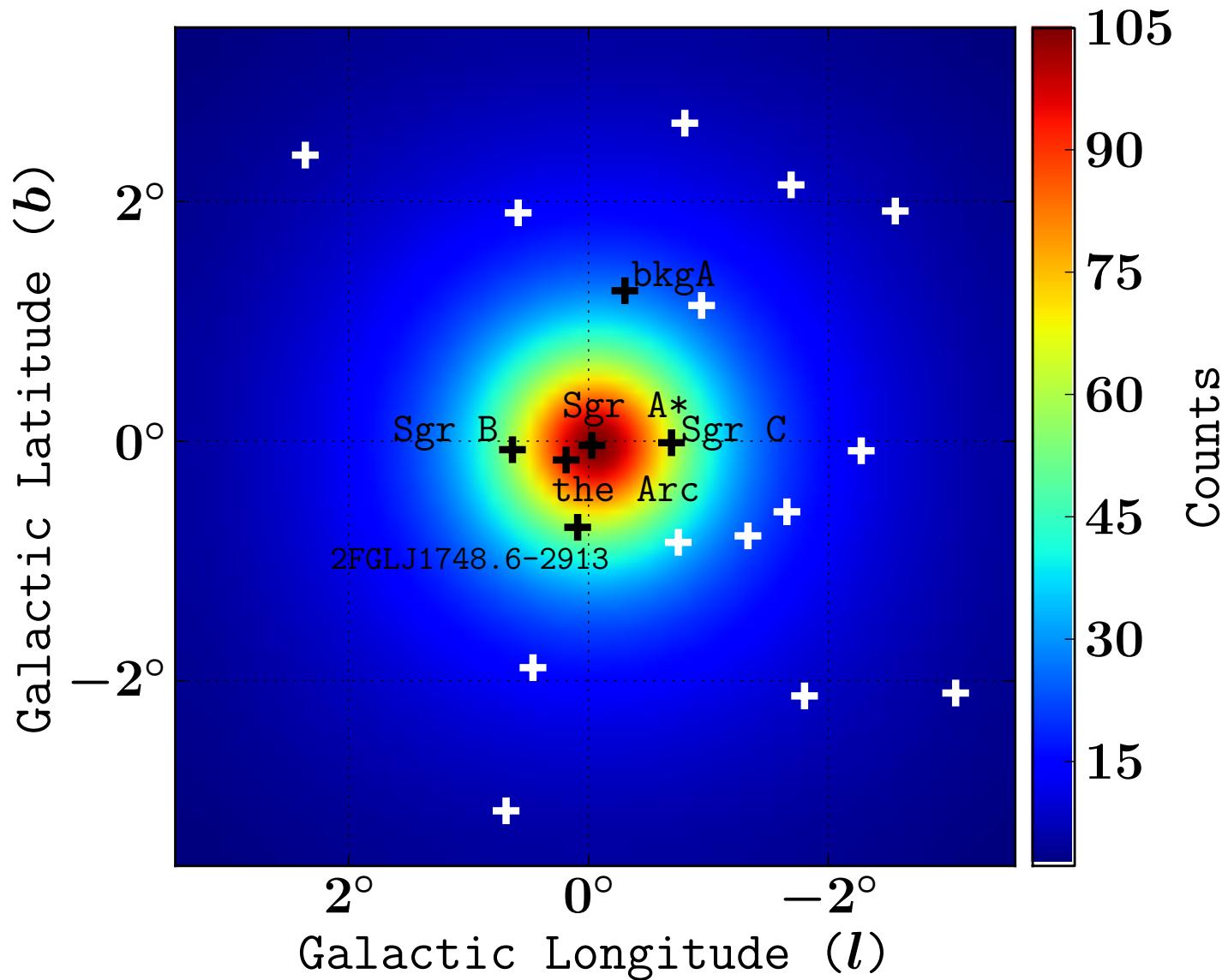
where we fixed  $r_s=23.1$  kpc,  
 $\alpha=1$ , and  $\beta=3$ .



# Spatial Distribution

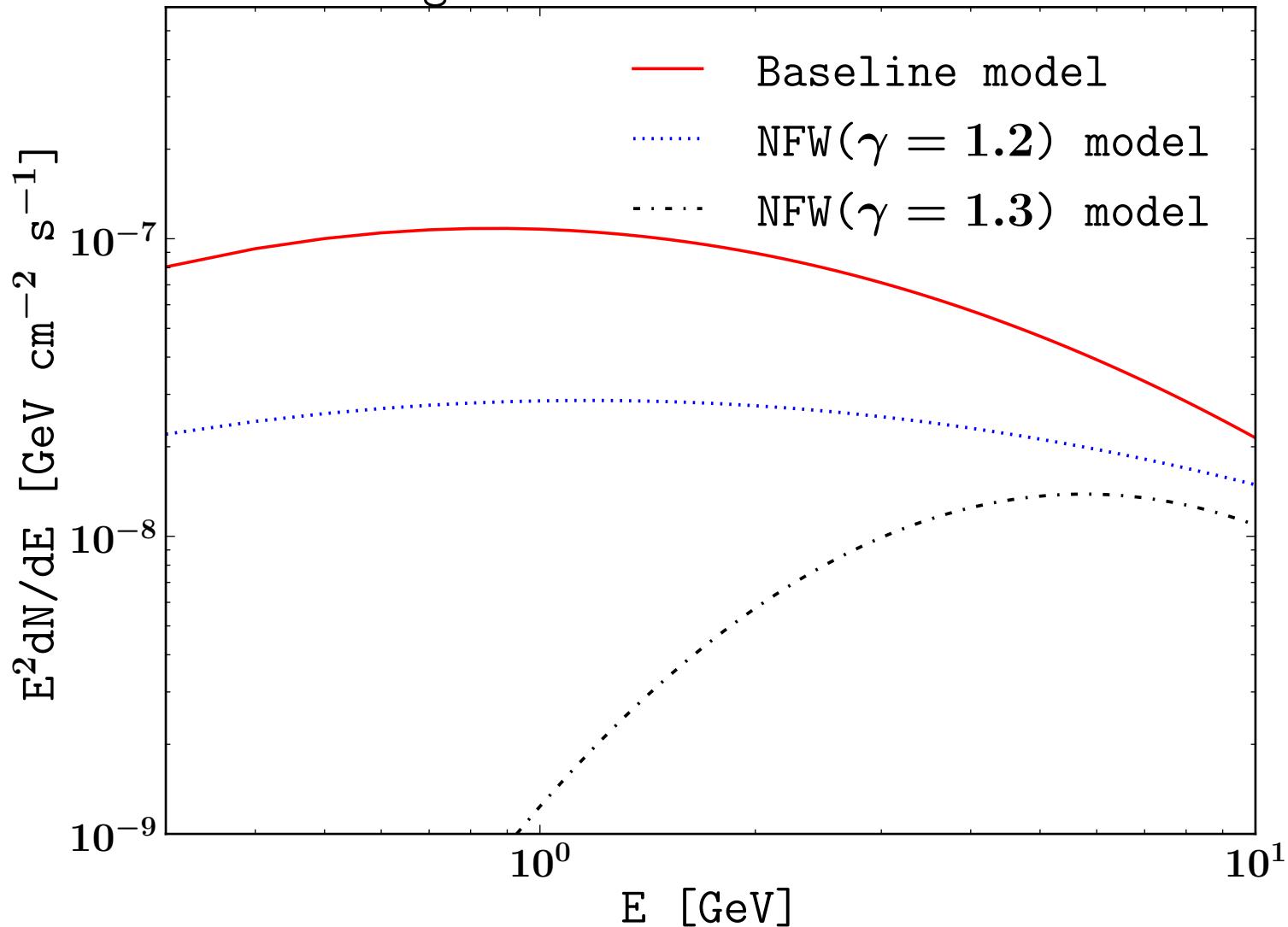


# Dark Matter (or MSP?)



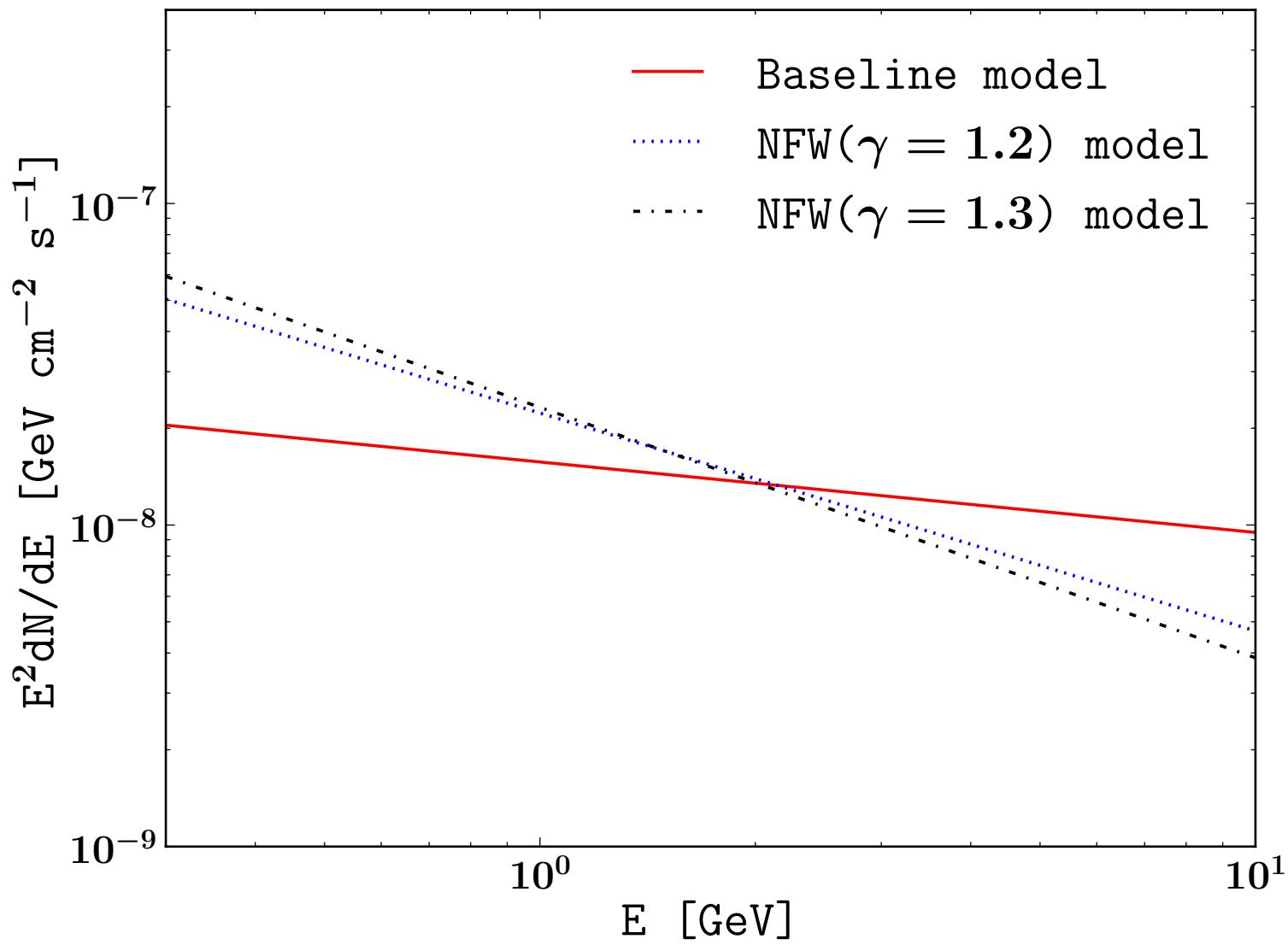
# Degeneracy

Sgr A\* - 2FGLJ1745.6-2858

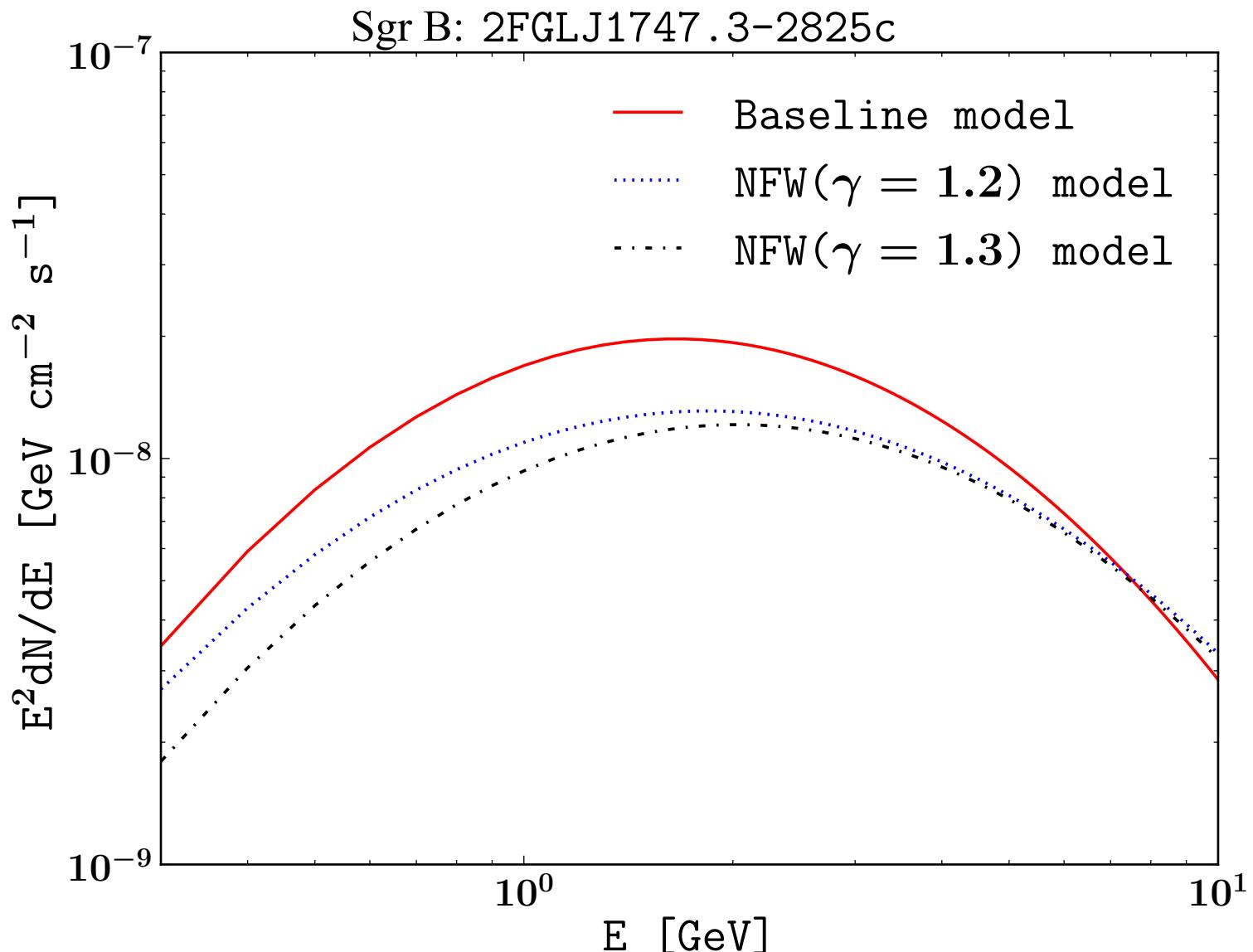


# Degeneracy

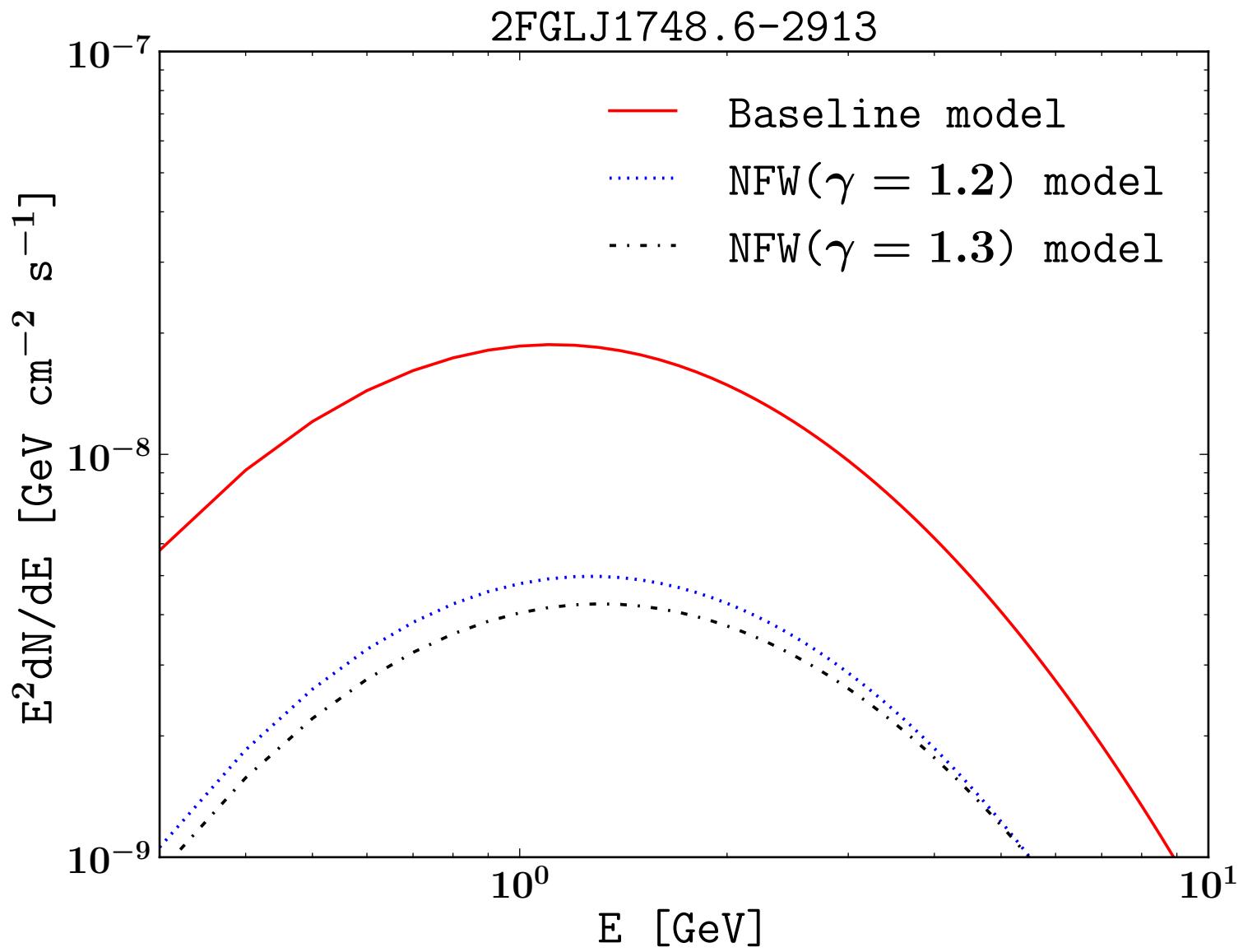
The Arc: 2FGLJ1746.6-2851c



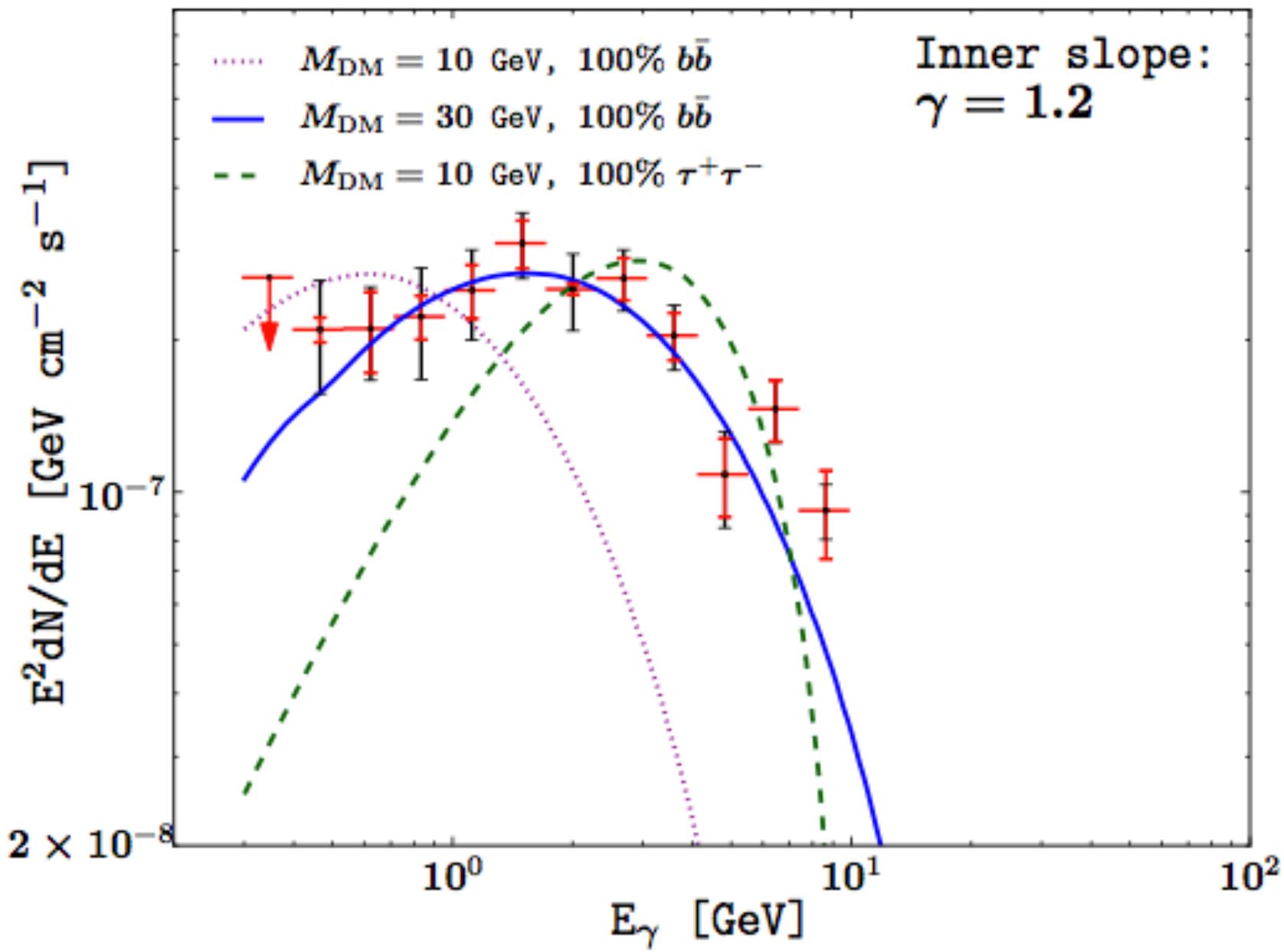
# Degeneracy



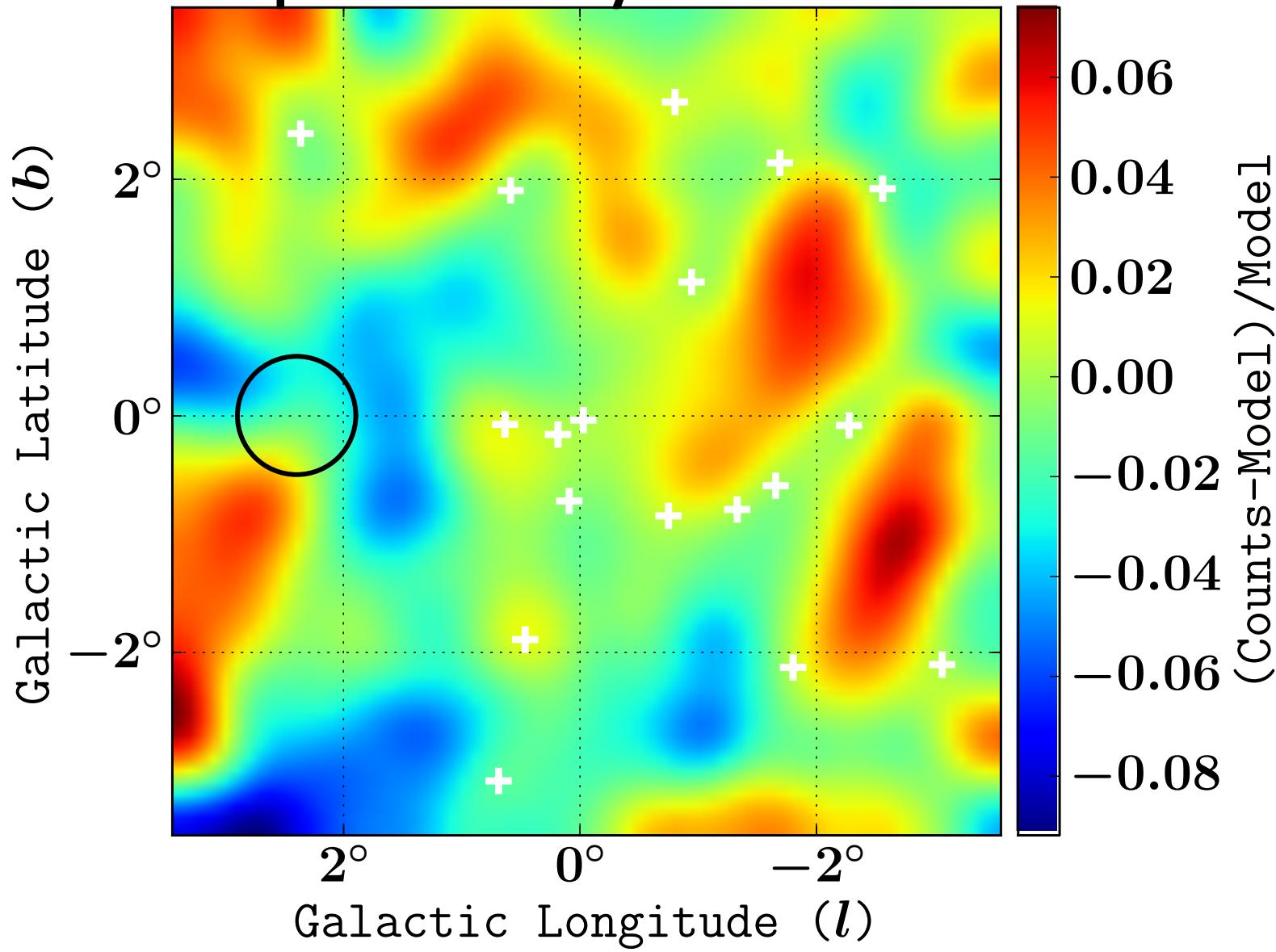
# Degeneracy



# Spectrum

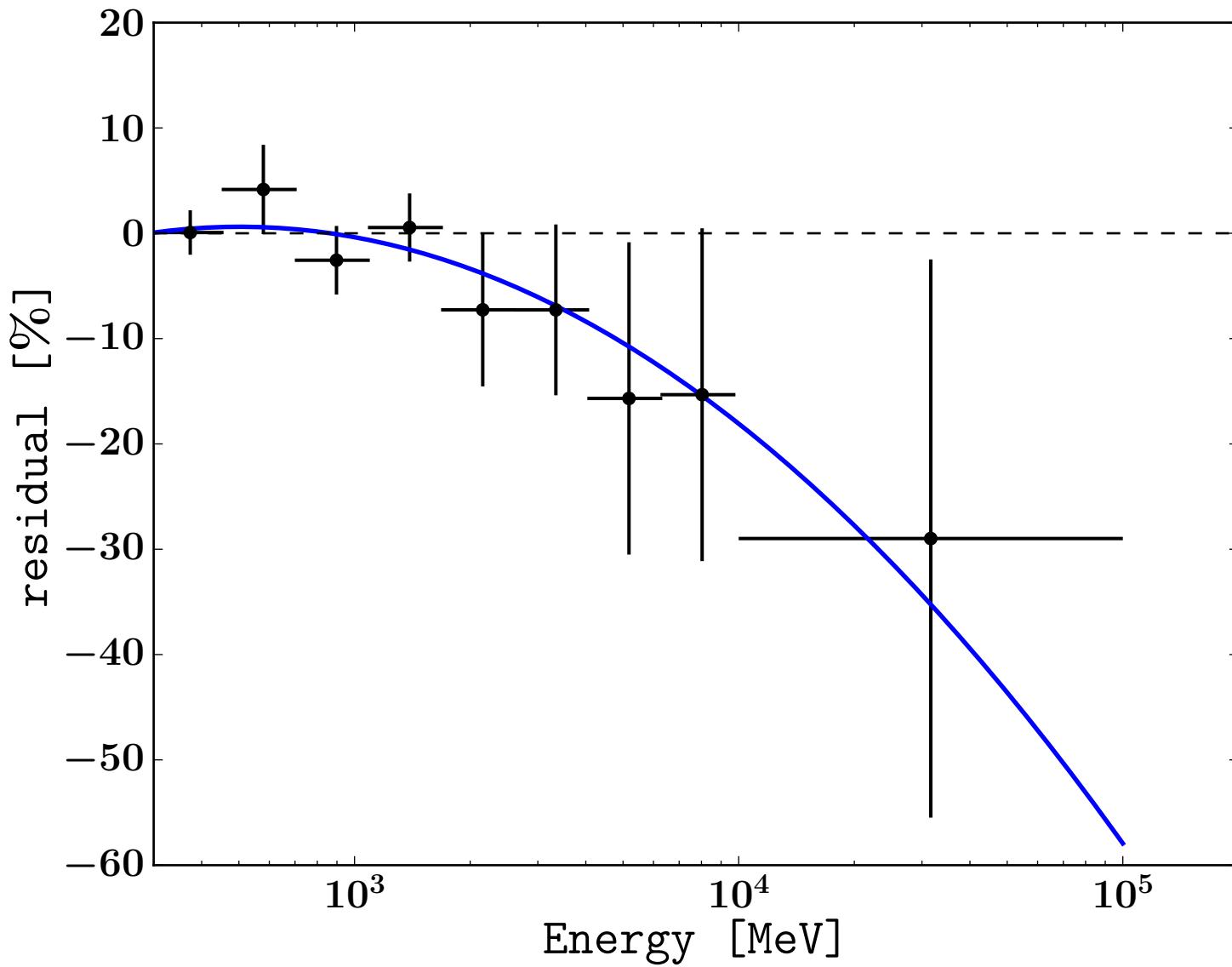


# Spectral Systematics

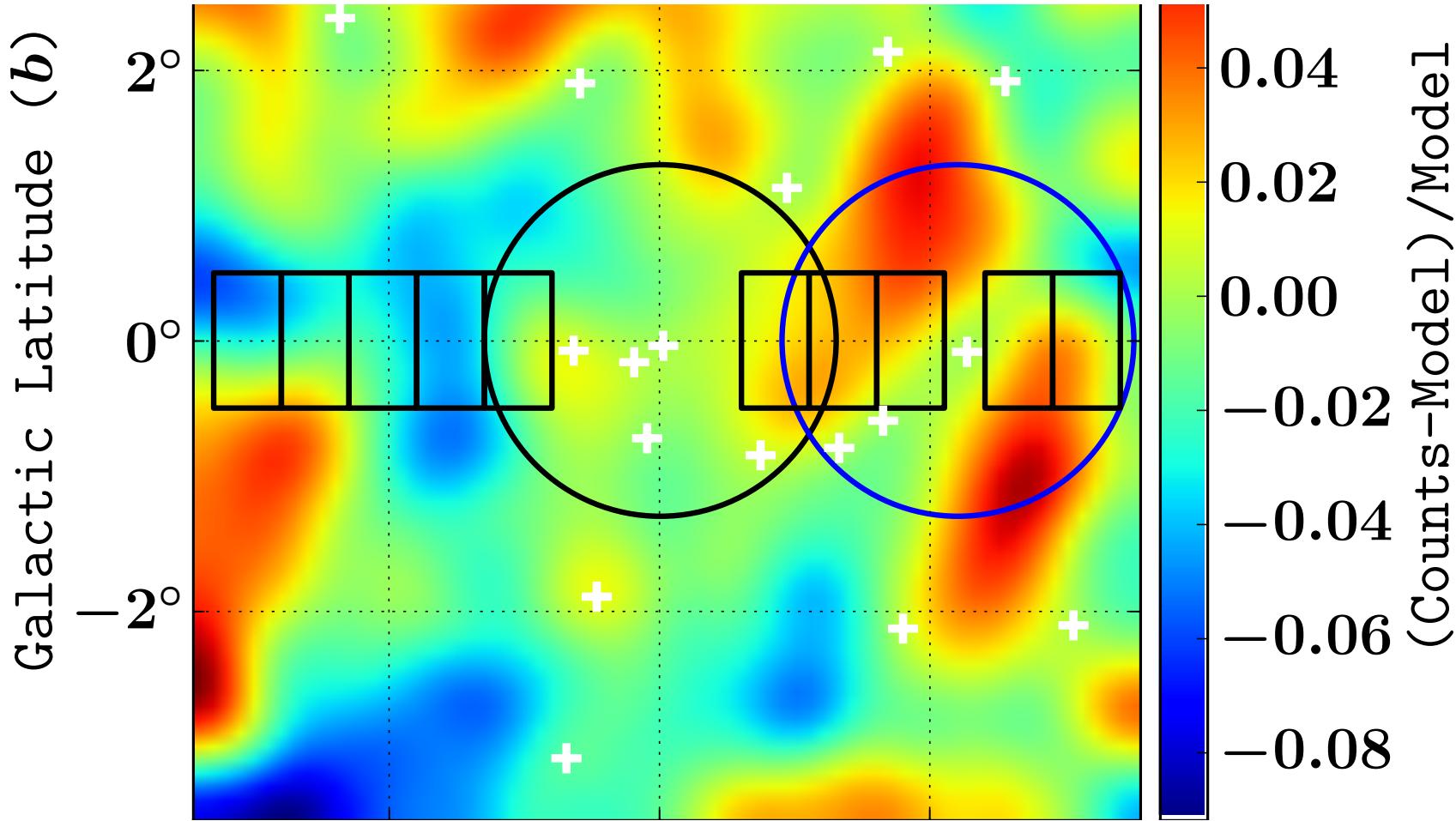


Similar method to: Fermi-LAT Collaboration, "Fermi-LAT Study of Gamma-ray Emission in the Direction of Supernova Remnant W49B", 2010.

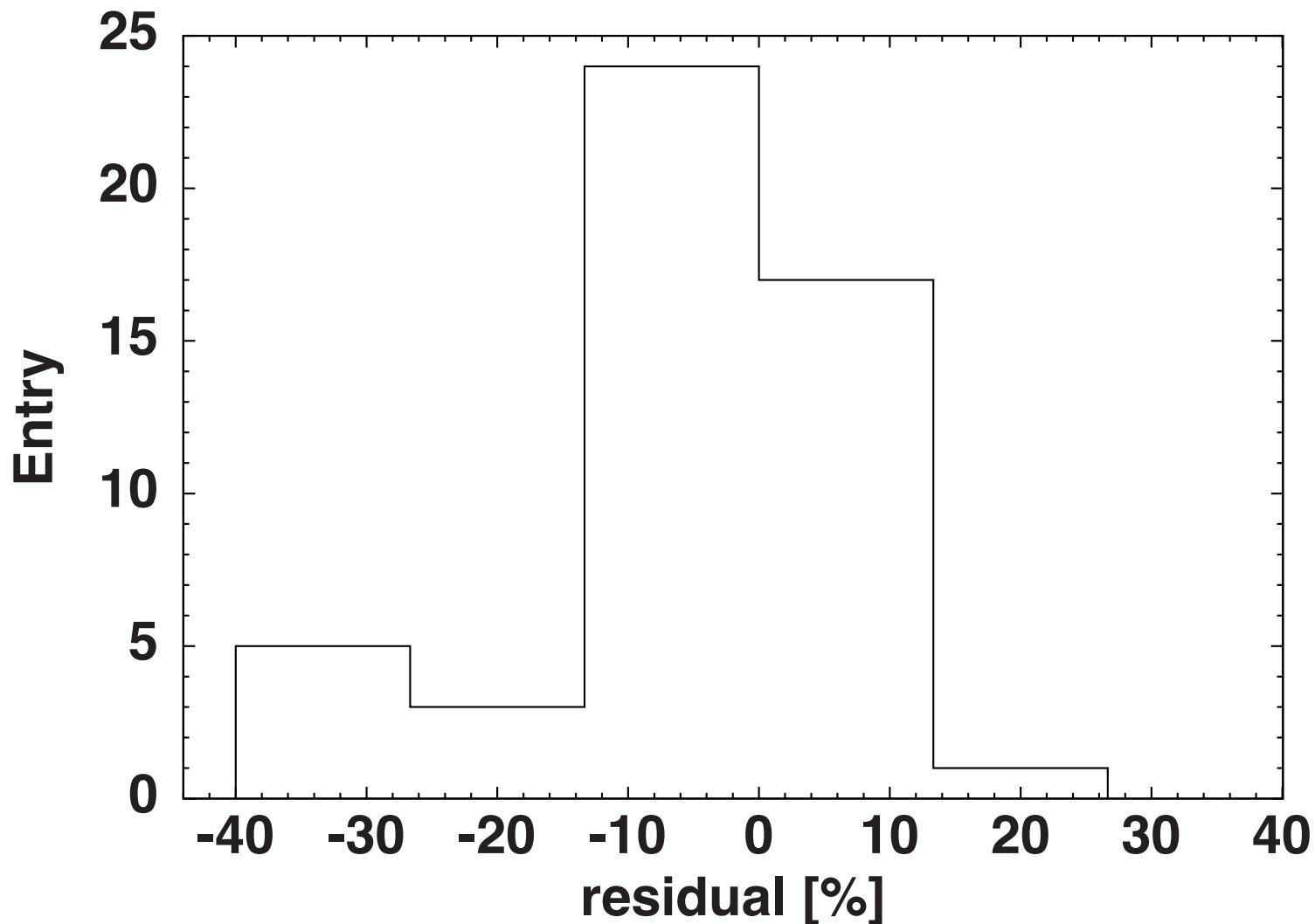
# Spectral Systematics



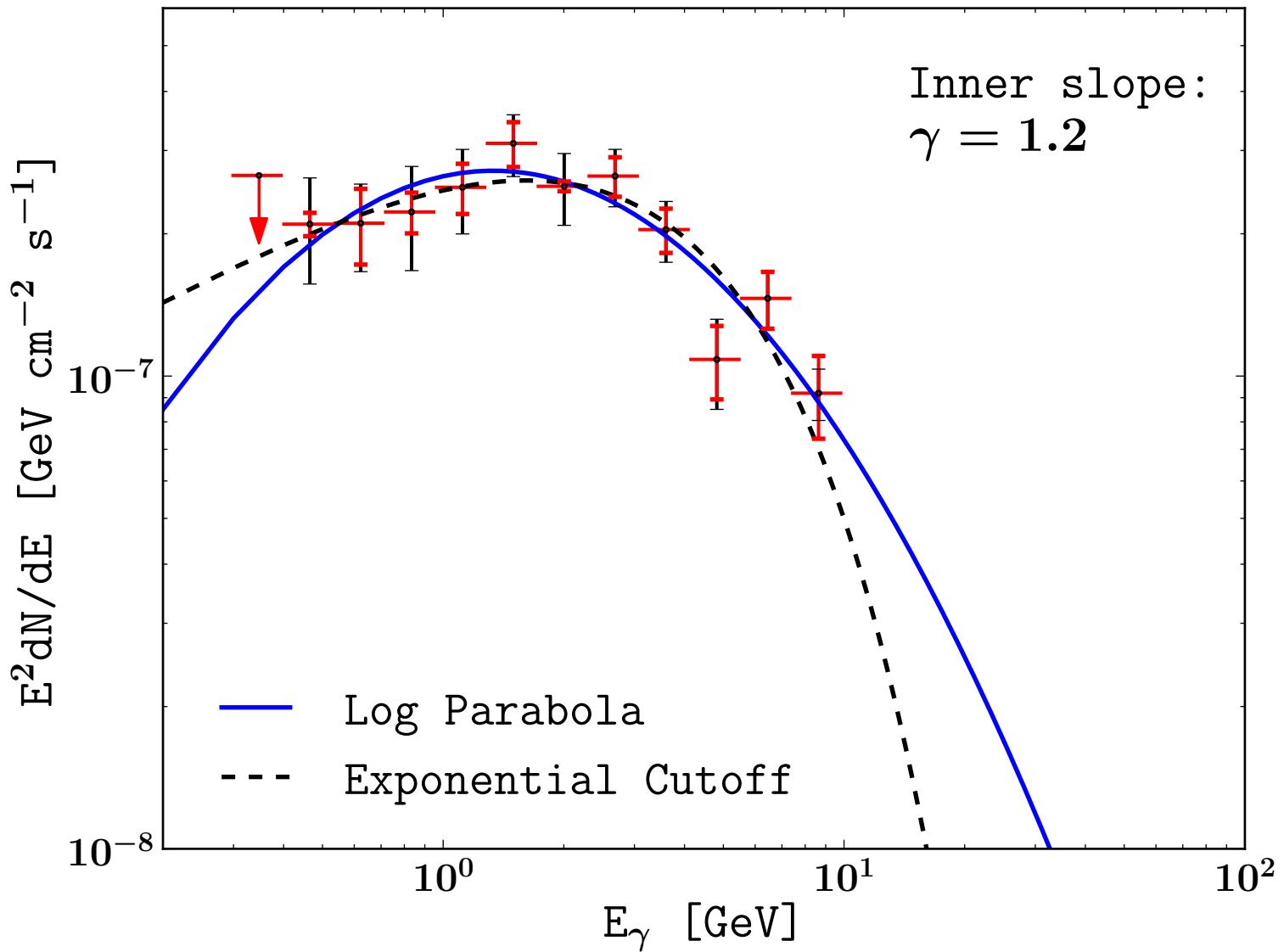
# Spatial Systematic Errors



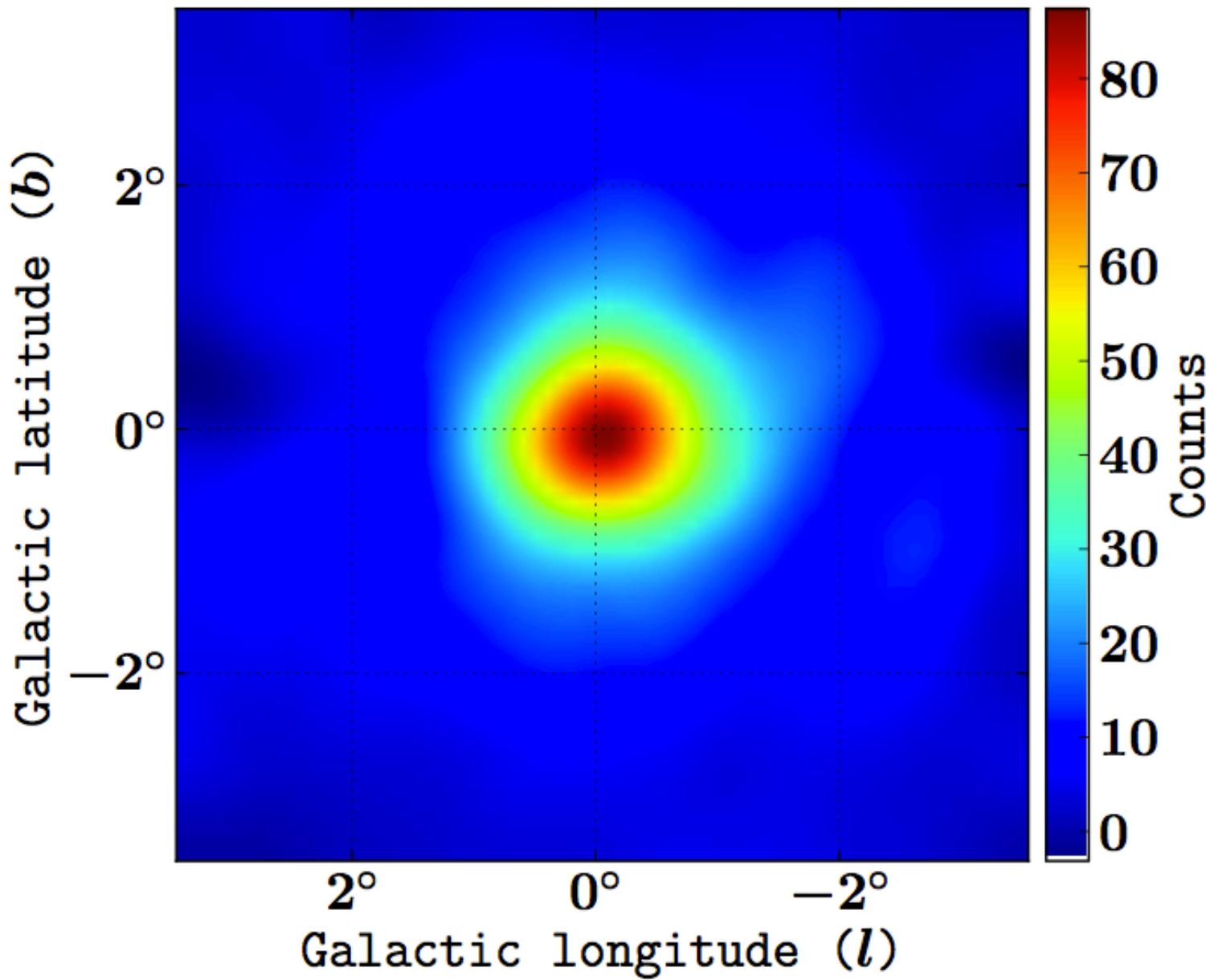
# Spatial Systematic Errors



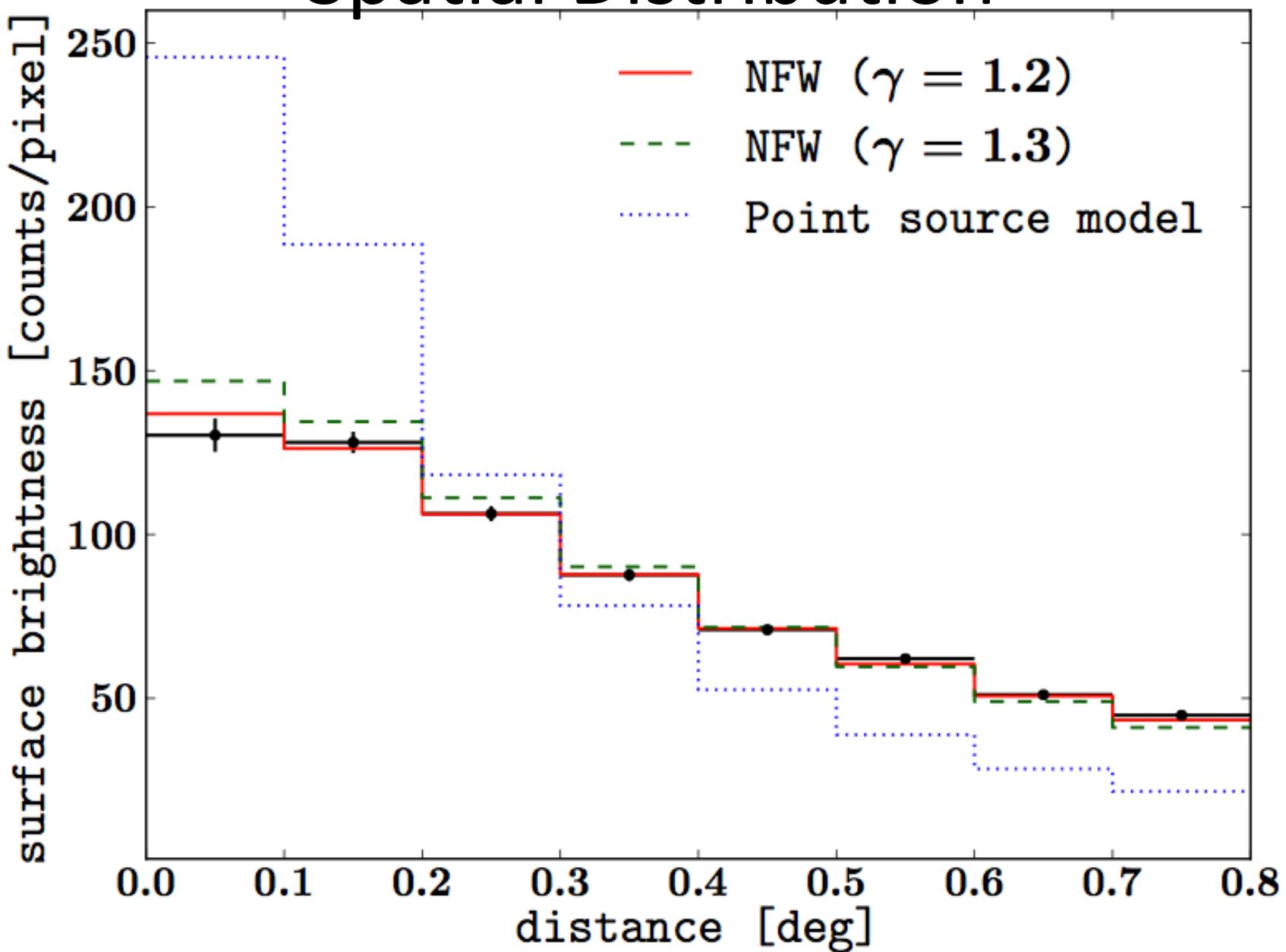
# Millisecond Pulsar Spectrum



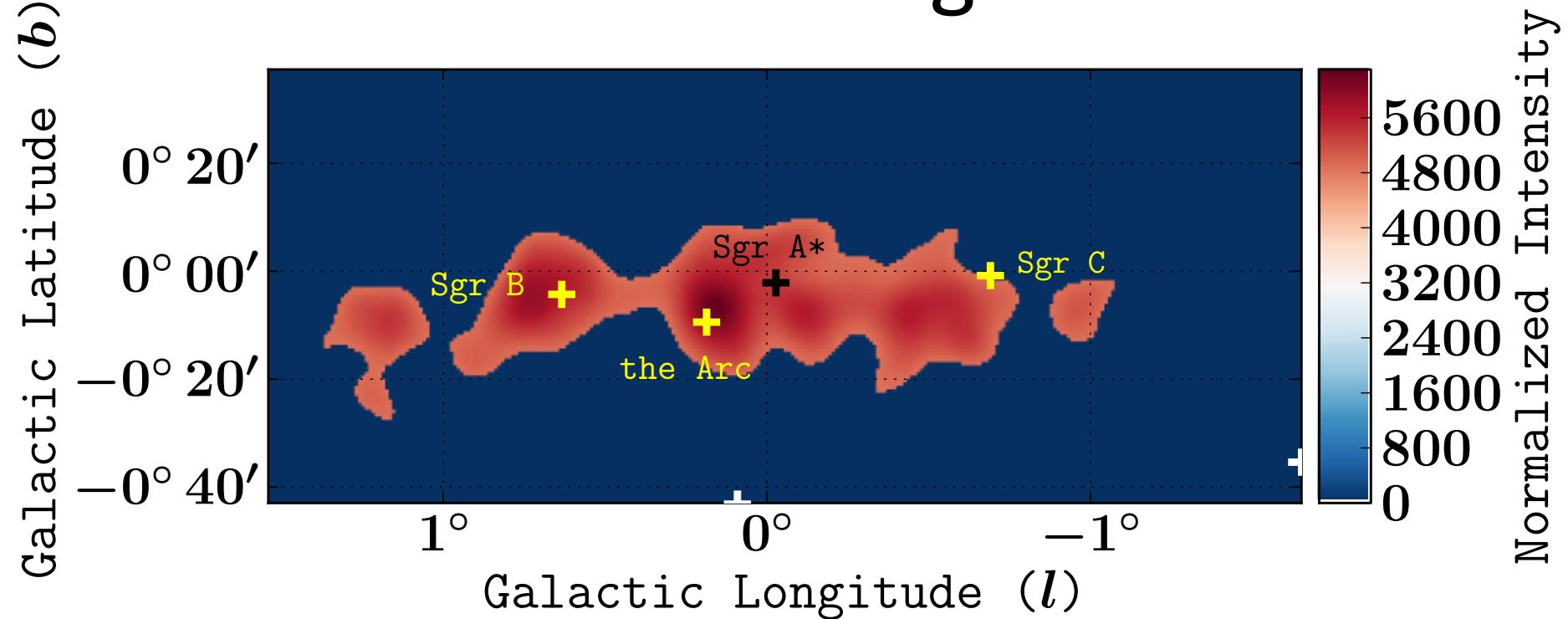
# Spatial Distribution



# Spatial Distribution

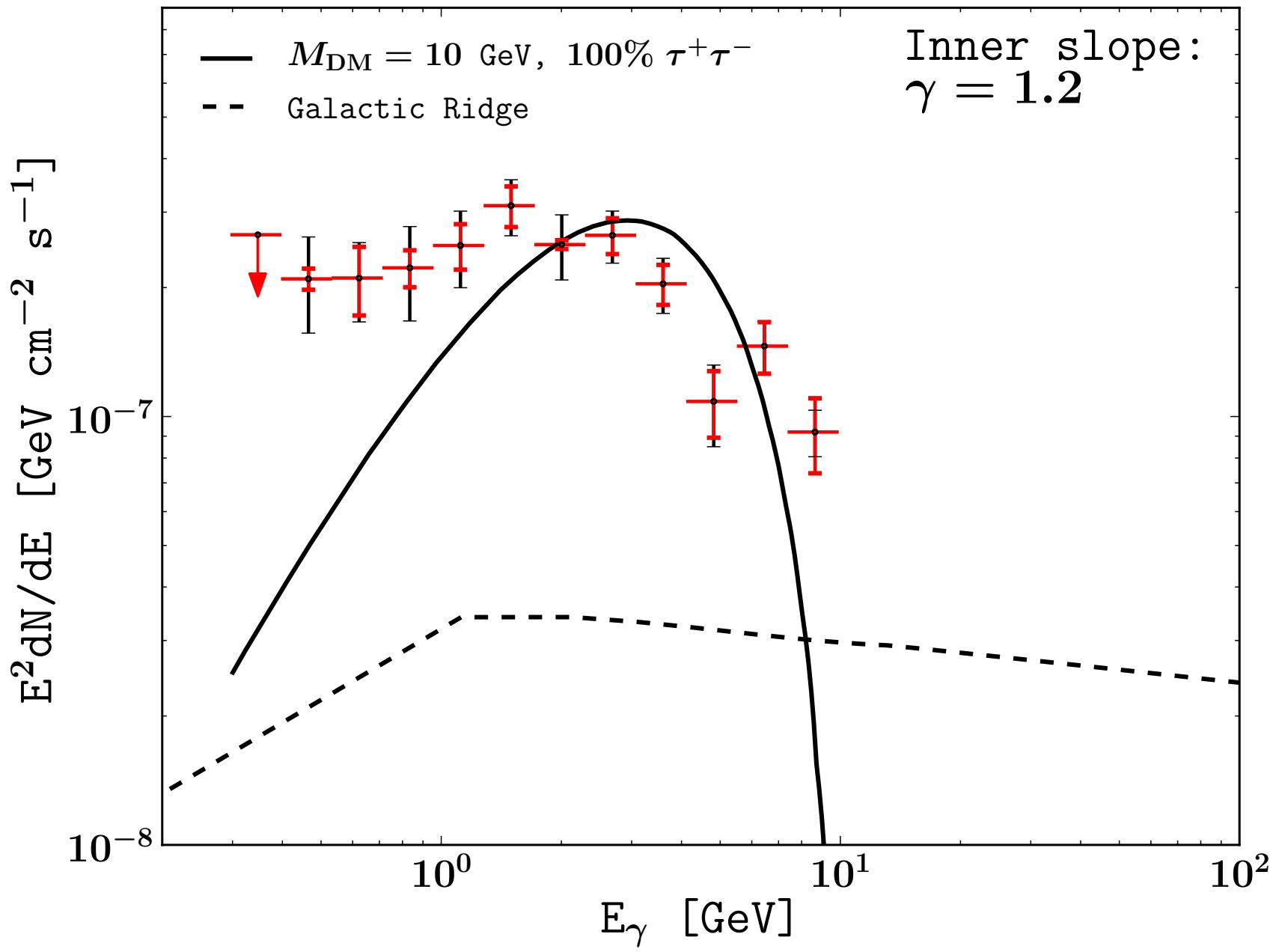


# HESS Ridge

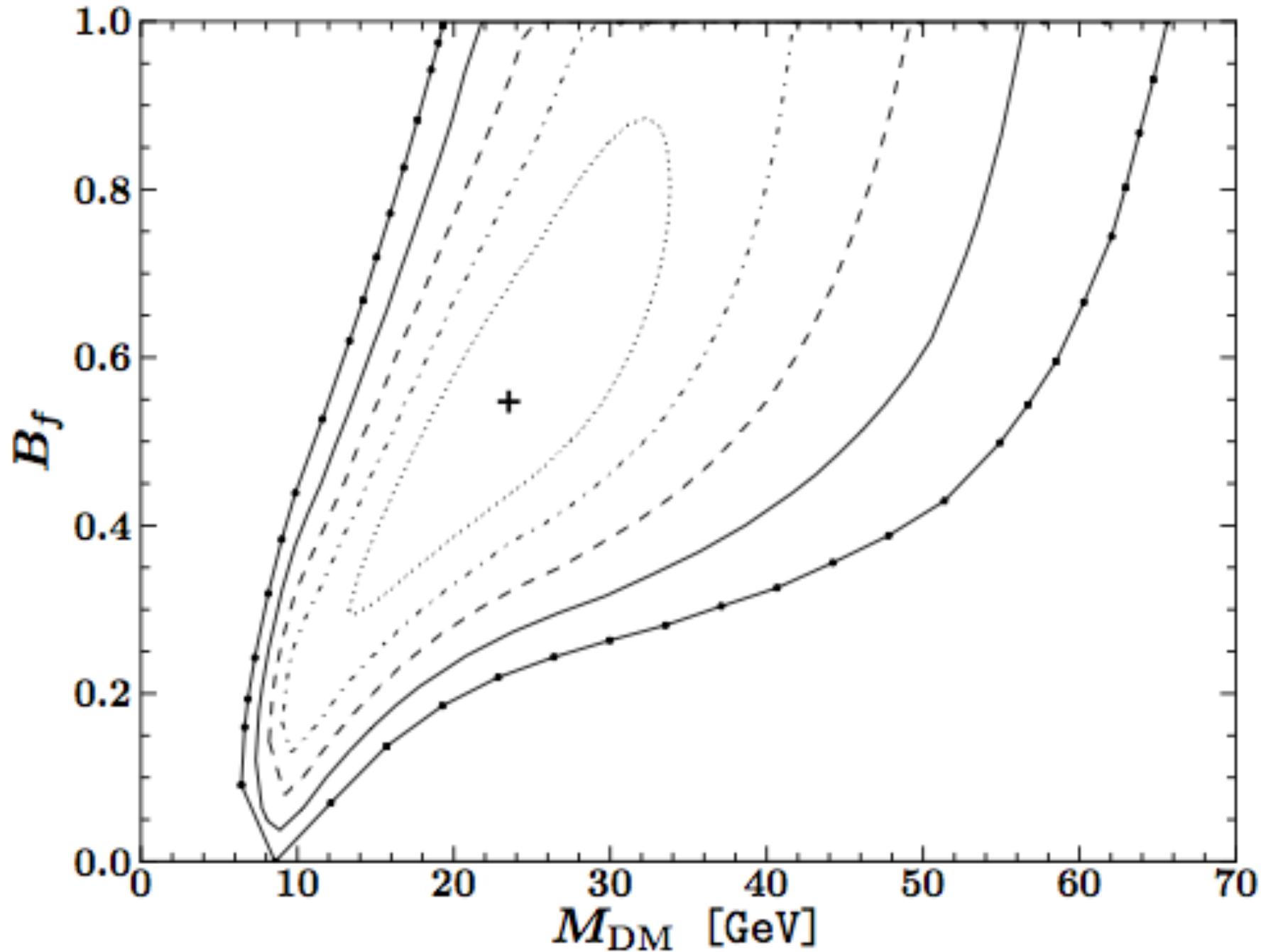


- Is not degenerate with DM due to different spatial morphology.
- We reproduce results of Yusef-Zadeh+2013 broken power law fit when we replace the three point sources associated with the Arc, Sgr B and Sgr C with the HESS ridge.

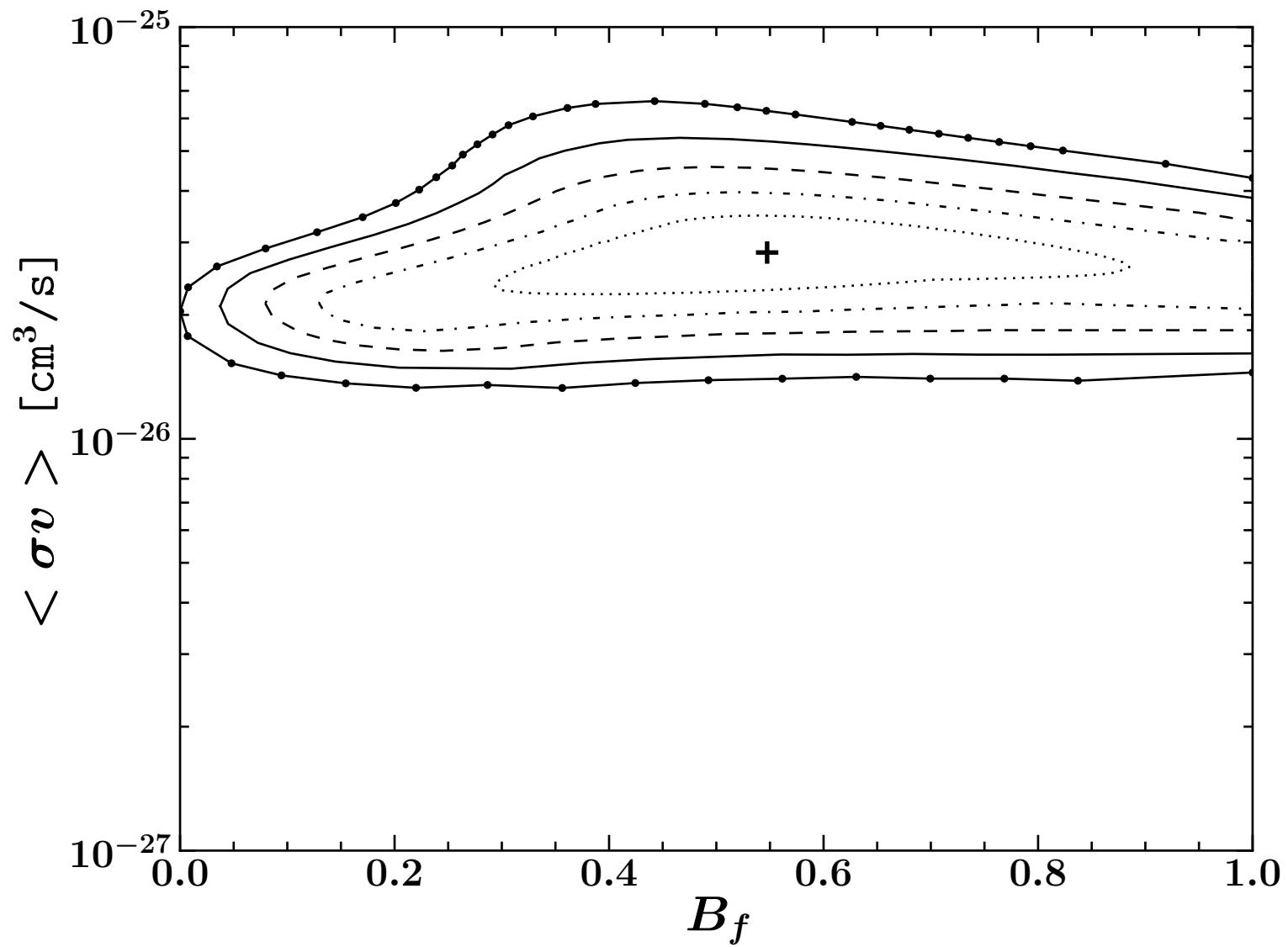
# HESS Ridge



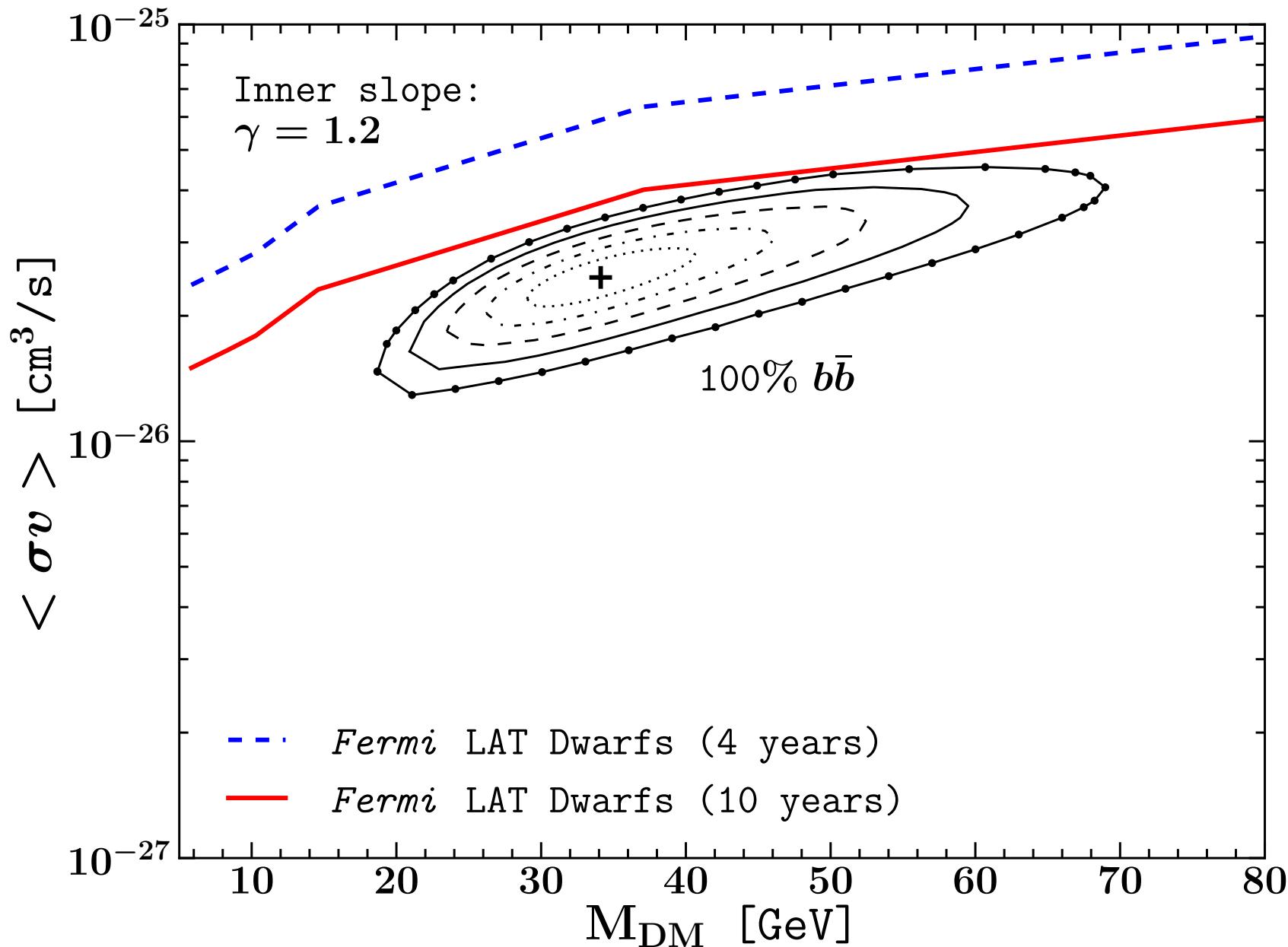
# Confidence Intervals



# Confidence Intervals



# Compare Fermi-LAT Collaboration, arxiv:1310.0828.



# Millisecond Pulsars

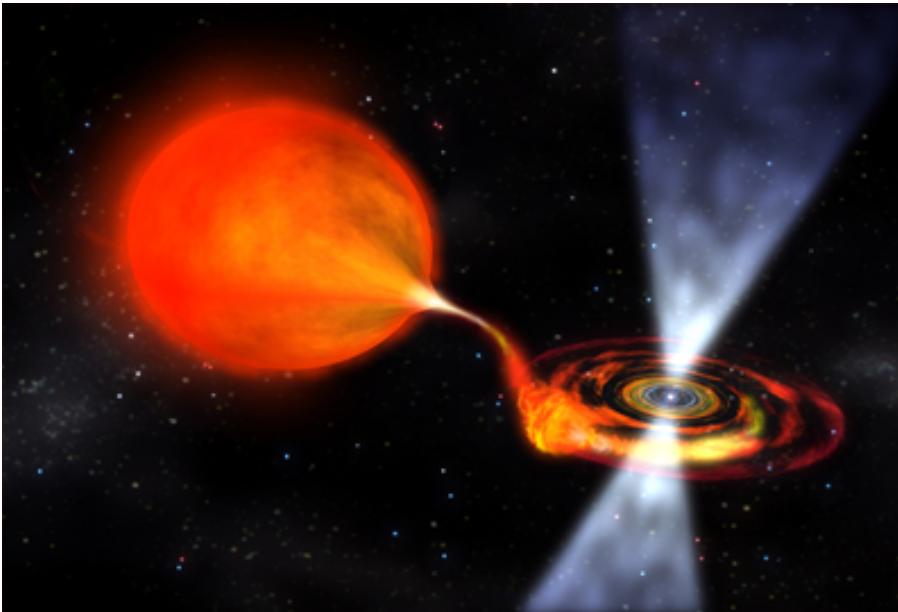
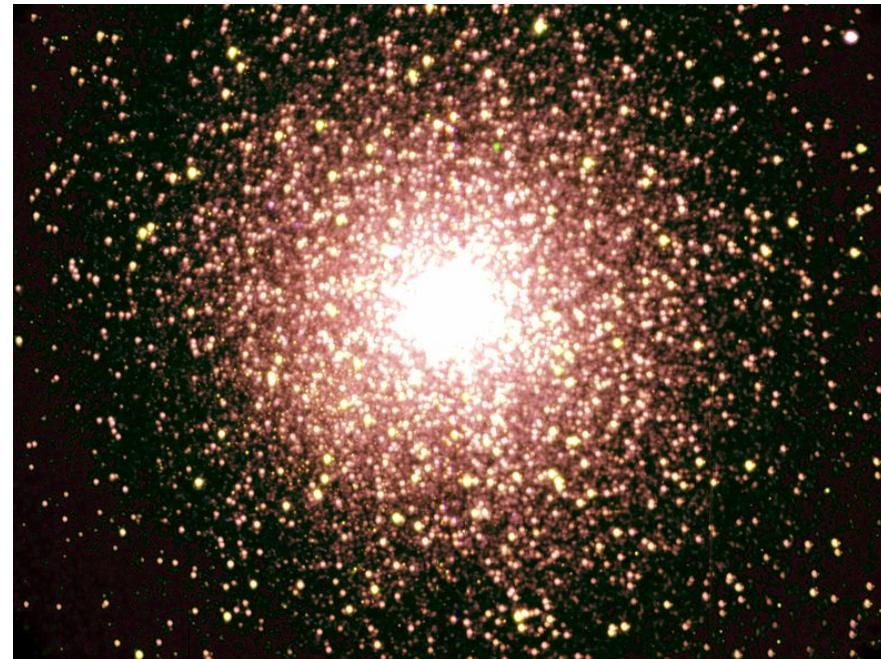


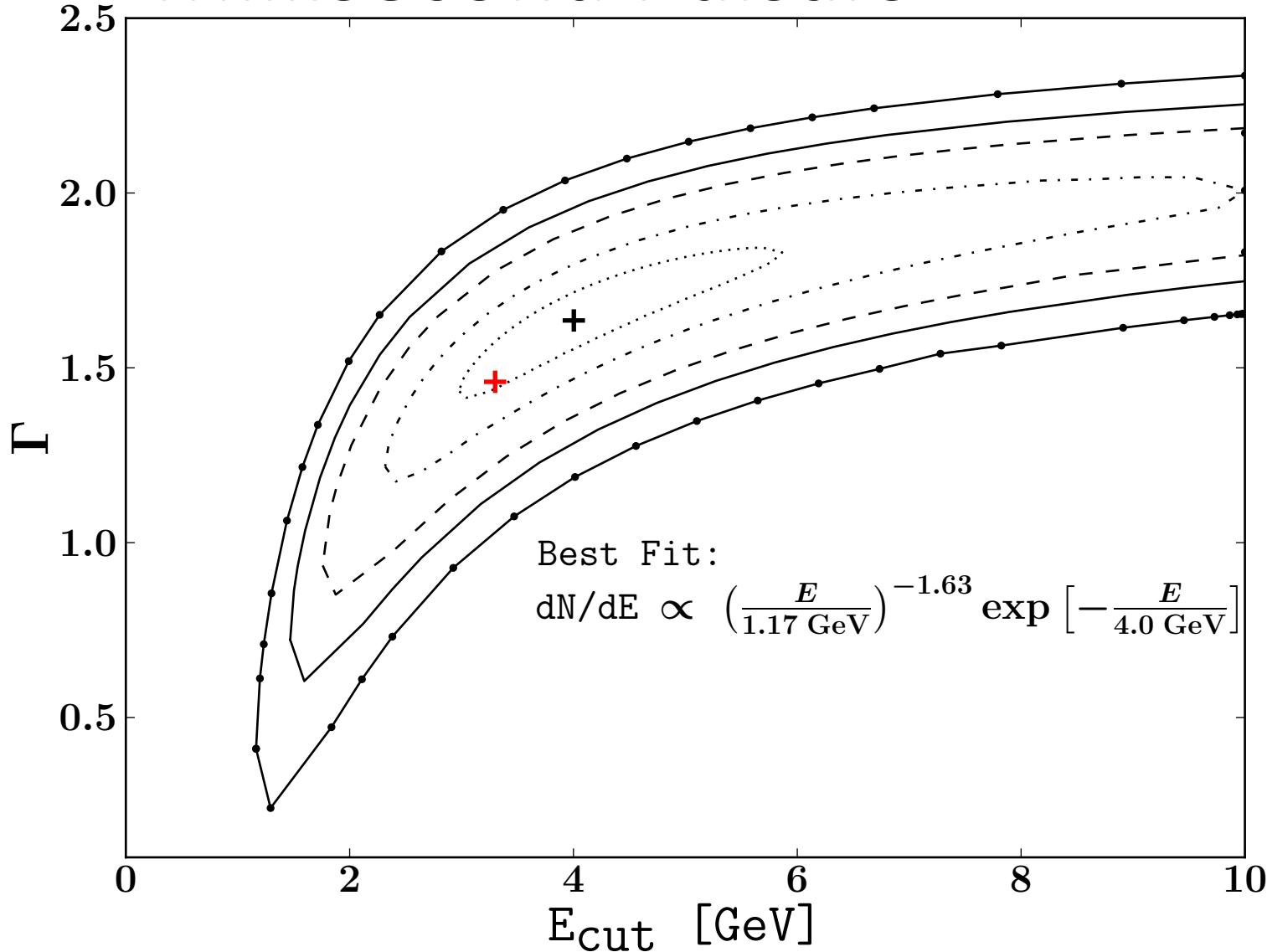
Image: NASA/Dana Berry.



Globular cluster 47 Tucanae (also known as NGC 104). Photo taken by the [Southern African Large Telescope \(SALT\)](#)

- A unresolved population of rapidly rotating neutron stars, known as millisecond pulsars, have the right spectral and spatial distribution to explain Galactic center excess (Abazajian and Kaplinghat (2012)).

# Millisecond Pulsars



# Millisecond Pulsars

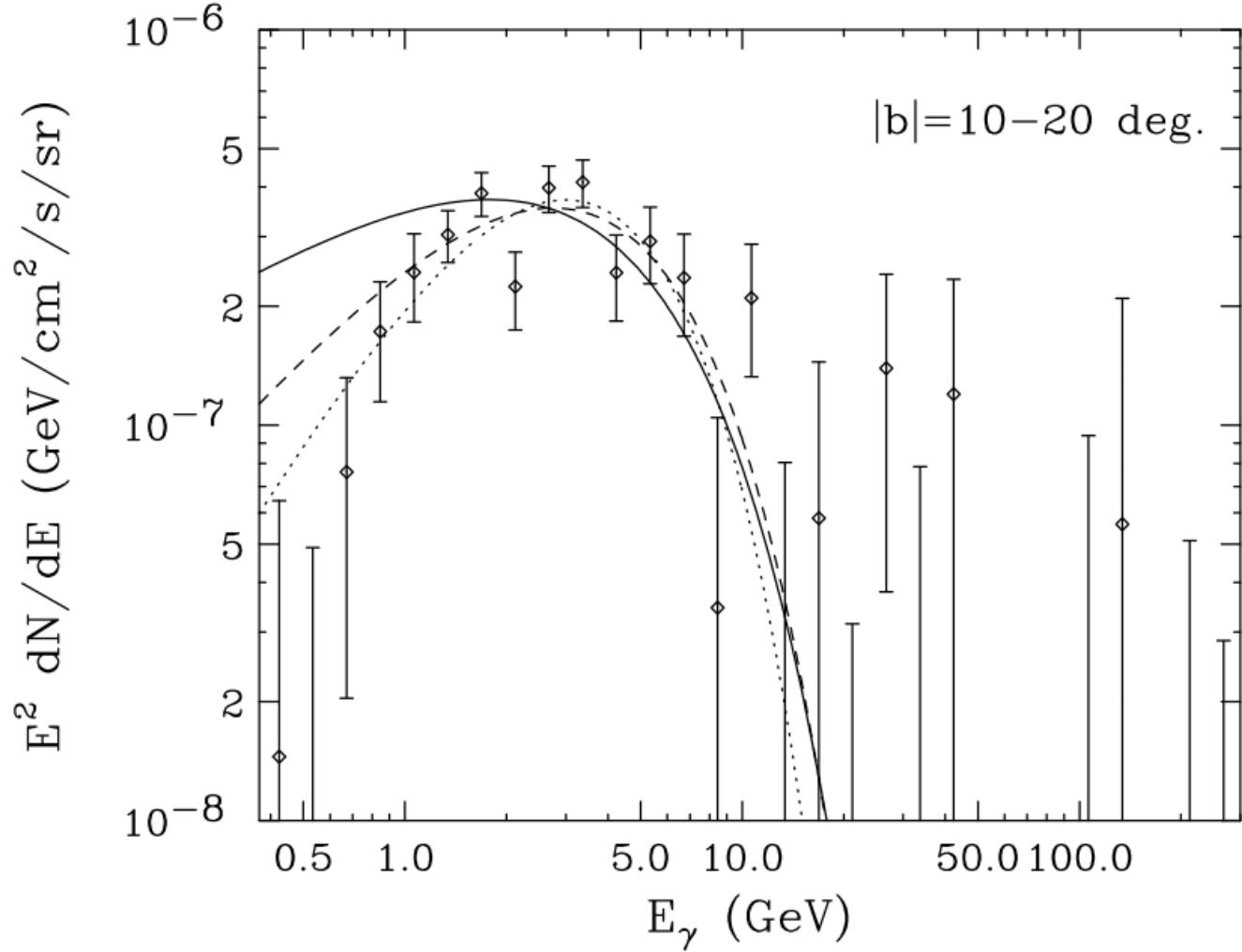
- We confirm between 1000 and 2000 millisecond pulsars (MSPs) could account for the Galactic center excess emission.
- By estimating the core collapse supernovae rate and the fraction of neutron stars that are recycled to be pulsars (0.1), the number of MSPs in 150 pc of the Galactic center is estimate to be of order 5000 (Wharton+2012).
- Currently can't easily resolve MSPs in Galactic center due to dispersion effects. It may be possible with the Square Kilometer Array (SKA).
- Andromeda has a distribution of low mass x-ray binaries (LMXB) consistent with  $\gamma=1.2$  in a  $\rho^2$  generalized NFW model (Abazajian&Kaplinghat 2013).
- LMXB and MSP are thought to be different phases of the same population.

# Millisecond Pulsars

- Within the dense molecular clouds of the central few hundred parsecs (“central molecular zone”), there is a compact region named the “nuclear bulge” .
- Estimates of the stellar content based on the near infra-red luminosity suggest a total stellar mass of  $\sim 10^9 M_{\odot}$  and most this mass is within the inner 1 degree.
- This is  $\sim 1000$  times more than the stellar mass in 47 Tuc globular cluster and the required number of MSPs is about  $\sim 20$  times more than that in 47 Tuc. This is plausible despite the large velocity dispersion in the Galactic Center given the higher stellar densities in the Galactic nuclear bulge.

# Millisecond Pulsars

- However, the excess emission may also be visible out to about 3kpc from the Galactic center (Hooper&Slatyer 2013) which would be hard to explain with MSPs given the number of resolved MSPs seen by Fermi LAT (Hooper +2013).



# Conclusions

- Analyzed Fermi-LAT Galactic center excess emission taking into account degeneracy with point sources and systematics in diffuse Galactic background.
- Confirmed 30 GeV DM annihilating into quarks is a good fit, but found annihilating purely into leptons was not a good fit.
- Found 1000 to 2000 unresolved millisecond pulsars was also a good fit.
- SKA observations may eventually better constrain millisecond pulsar explanation.